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REON

ROCKET ENGINE OPERATIONS — NUCLEAR

RN-S-0171

N68-17267

A Report To

AEC-NASA SPACE PROPULSION OFFICE

NUCLEAR ENGINE ANALYSIS PROGRAM

VOL. I - TECHNICAL DISCUSSION AND PROGRAM NOMENCLATURE

Contract SNP-1 December 1964 NERVA Program

This is an
UNCLASSIFIED
NERVA Research and Development Report

UNITED STATES

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NUCLEAR ENGINE ANALYSIS PROGRAM
Vol. I - TECHNICAL DISCUSSION AND PROGRAM NOMENCLATURE

ROCKET ENGINE OPERATIONS – NUCLEAR

RELEASED FOR ANNOUNCEMENT
IN NUCLEAR SCIENCE ABSTRACTS

AEROJET-GENERAL CORPORATION
A SUBSIDIARY OF THE GENERAL TIRE & RUBBER COMPANY

RN-S-0171

ABSTRACT

The Nuclear Engine Analysis Program is an IBM 7094 digital computer program which simulates the steady-state operation of the NERVA hot-bleed engine over the full operational range of chamber pressures and temperatures. This program computes the energy balances for all engine components and for the entire engine, as required to satisfy the demanded chamber pressure and temperature. The program output consists of temperatures, pressures, and flow rates throughout the system. In addition, program output such as the turbine inlet temperature, turbine flow rate, hot-bleed flow rate, diluent flow rate, turbopump speed, pump specific speed, turbine power control valve position, nuclear power, engine thrust and specific impulse are obtained. The program is presently in production status and is being used extensively for steady-state analyses of the NERVA engine systems.

for W. D. Stinnett
REON Program Manager

Prepared by:

R. D. CoNine

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I. SUMMARY

The Nuclear Engine Analysis Program is an IBM 7094 digital computer program which simulates the steady-state operation of the NERVA hot-bleed engine over the full operational range of chamber pressures and temperatures. It computes the energy balances for all engine components and for the entire engine, as required to satisfy the demanded chamber pressure and temperature. The program output consists of temperatures, pressures, and flow rates throughout the system. In addition, program output such as the turbine inlet temperature, turbine flow rate, hot-bleed flow rate, diluent flow rate, turbopump speed, pump specific speed, turbine power control valve position, nuclear power, engine thrust and specific impulse is obtained.

Subroutines have been constructed to simulate the operation of each engine component. Included in the program are hydrogen properties subroutines which provide a complete representation of the thermodynamic and transport properties of hydrogen. All component calculations are performed in enough detail to provide an accurate determination of the energy added or subtracted from the fluid, the pressure drops, the flow rates, and the component operating temperatures. The goal is to show the effect of the component on overall system operation, to define the component operating conditions (i.e., entrance pressure, temperature, and flow rate) for the use of the component designers, and to determine the system operating constraints imposed by the various components.

The program begins to compute the system energy balance by assuming a pump discharge pressure and reactor power; then the required pump power is computed. The turbine inlet flow rate and temperature required to deliver

this pump power are obtained, including the effect of heat transfer between the diluent flow and the turbine inlet flow. The heat addition, pressure drop, and flow distribution in the nozzle, reflector, shield, and core are then computed. If the core exit pressure and temperature do not agree with the demanded chamber pressure and temperature, the assumed pump discharge pressure and reactor power are changed and the computation repeated until agreement is reached. When the calculation has converged, the significant engine system performance characteristics are calculated.

II. PROGRAM DESCRIPTION

A. PROBLEM

The objective of the Nuclear Engine Analysis Program is to analyze the NERVA Hot-Bleed Engine, over the entire range of steady-state operation, in sufficient detail to (1) define the effect of each component on the overall system operation, (2) define the component operating conditions, and (3) determine the system operating constraints imposed by the various components. The program accomplishes this through the use of subroutines which have been constructed to simulate the operation of each engine component. All of these component calculations are performed in enough detail to provide an accurate determination of the energy added or subtracted from the fluid, the pressure drops, the flow rates, and the component operating temperatures. The problem which this program solves is the calculation of those parameters which describe the steady-state operation of the NERVA Hot-Bleed Engine.

In Figure 1, the physical and functional arrangement of the NERVA Hot-Bleed Engine components may be seen. The basic flow pattern of the propellant fluid is from the propellant tank through the propellant shut-off valve and the pump inlet line to the pump. The pump, which is directly driven by the turbine, boosts the pressure of the propellant and discharges it into the pump discharge line. The propellant then flows through the coolant tubes of the exhaust nozzle. From there, the fluid flows through a nuclear reflector and an internal nuclear shield into the reactor core. After flowing through the reactor core, the main propellant flow passes through the exhaust side of the nozzle and exhausts to the atmosphere. The turbine is driven by bleed gases which are obtained by mixing fluid obtained from the nozzle chamber through a hot bleed port with diluent fluid obtained from the shield inlet plenum. The turbine inlet line is cooled by a counter-flow heat exchanger in which the diluent is used as a coolant before it is mixed with the hot-bleed gases. The turbine drive fluid exhausts to the atmosphere through turbine exhaust nozzles. Table 1 shows the subscripts which are used to define engine locations for calculations internal to the Nuclear Engine Analysis Program.

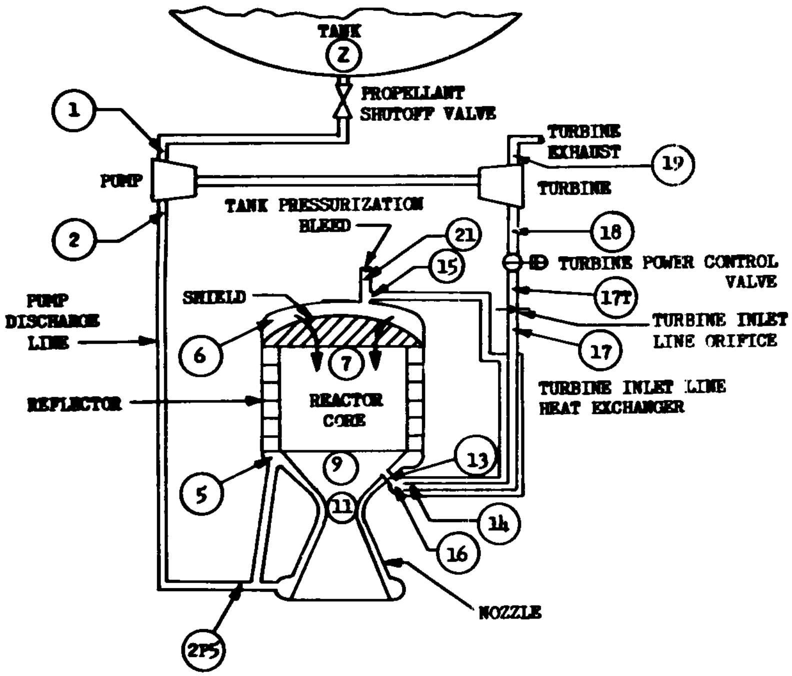

Figure 1

Cycle Schematic Diagram, NERVA Hot-Bleed Engine

TABLE 1

STATION DESIGNATIONS

Symbol	Location
Z	Propellant tank
1	Pump inlet
2	Pump discharge
2P5	Pump discharge line outlet (nozzle inlet)
5	Reflector inlet (nozzle exit)
6	Shield inlet (reflector exit)
7	Core inlet (shield exit)
9	Computed chamber conditions
11	Nozzle throat
14	Conditions just after mixing of diluent and hot bleed in the hot bleed port
15	Inlet to diluent side of turbine inlet line heat exchanger
16	Diluent orifice inlet
17	Turbine inlet line orifice inlet
17T	Turbine power control valve inlet
18	Turbine inlet
19	Turbine exhaust
21	Tank pressurization bleed conditions
C	Demanded chamber conditions

The chamber temperature of the propellant may be controlled by varying the power level of the reactor, which, in turn, is controlled by changing the position of the reactor control rods. The chamber pressure of the propellant may be controlled by adjusting the position of the turbine power control valve. The turbine power control valve, by controlling the amount of flow through the turbine, adjusts the energy supplied to the pump and, therefore, the pressure level of the entire flow system.

The functional arrangement of the engine components, and the interrelationships among the components, may be seen more clearly by referring to Figure 2. In this diagram, each engine component, or significant part of a component, is indicated by a block. The flow of functions among the components is indicated by lines linking the component blocks. Thus, propellant flow between components is indicated by the lines defining pressure (P), temperature (T), and flow rate ($\dot{w}$) between components. The other lines describe flow of other functions, such as heat flow (q''), nuclear heat generation (n), valve position (ϕ), turbopump speed (N), and torque (M).

The goal in constructing the Nuclear Engine Analysis Program has been to write a digital computer program which solves the system parameters for the particular configuration given in the functional diagram. Although the program is basically limited to the configuration given in Figure 2, several configuration options are available. First, a nozzle skirt may be added in which there is flow in the coolant tubes parallel to that in the main nozzle coolant tubes. Second, the diluent extraction point may be at any of three locations: the nozzle inlet plenum, the reflector inlet plenum, or the shield inlet plenum. Also, several options are available for different turbine and pump configurations. Finally, because the program has been written by extensive use of subroutines, rearrangement of the subroutines to allow analysis of different basic configurations is relatively simple and has been done several times in the past.

A sample input-output for a complete program run is given in Appendix B. All intermediate iterations are printed by the program, and are included in Appendix B as an example of a typical program iteration sequence. The converged solution is the last set of data and would normally be the only part of the output of interest.

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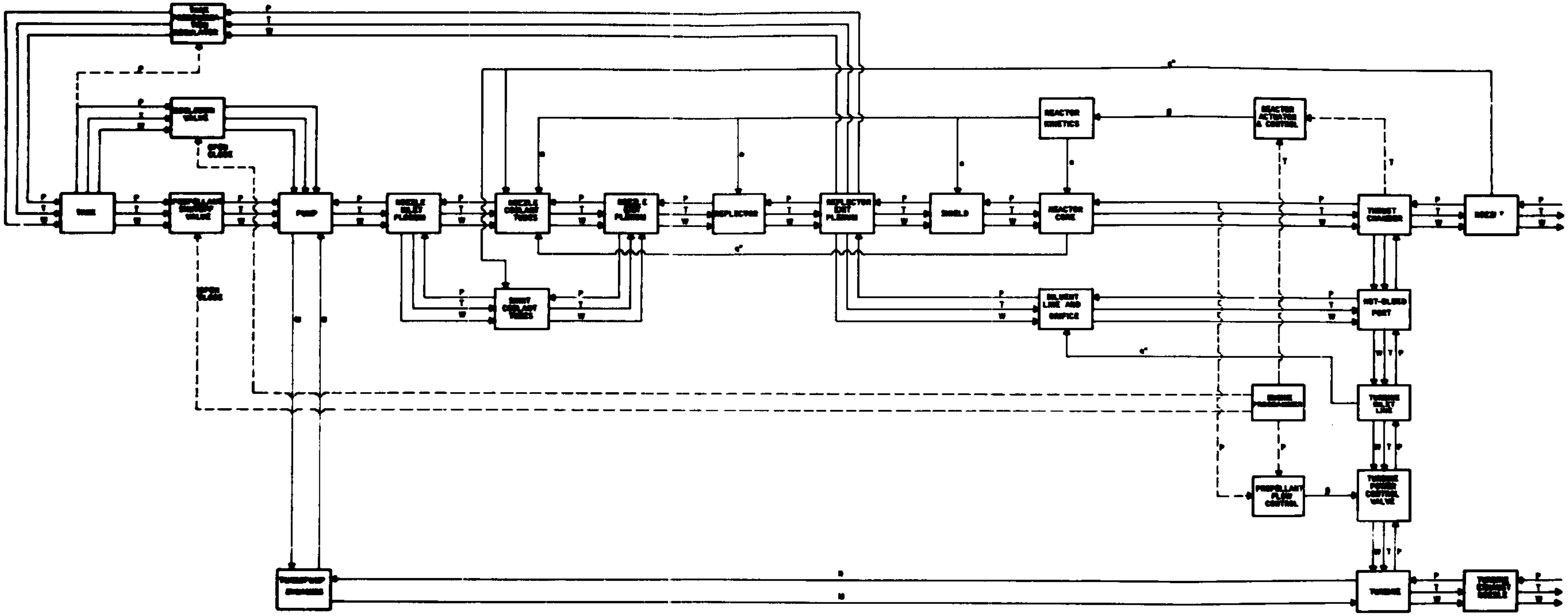

Figure 2

NERVA Hot-Bleed Engine Functional Diagram

B. METHOD OF SOLUTION

In general, a subroutine has been written to describe and compute the operations of each component block shown in Figure 2. Thus, subroutines have been written to describe the nozzle, reflector, shield, core, and turbopump. Within each of these subroutines, a great deal of leeway has been allowed in the detail which may be included for the component model. Thus for the reflector, shield, and core subroutines, each component may be split into several groups of parallel flow passages. Each type of flow passage may have any number of channels, but all channels of any flow type are assumed to be exactly the same. In the reflector, seven types of parallel flow passages are allowed. In the shield, five types of parallel flow passages are allowed. In the reactor core, five types of parallel fuel element channels and three types of parallel tie rod channels are allowed. The nozzle, reflector, shield, and core are each split into ten axial computational increments. In addition to these subroutines, there is a subroutine (or a portion of a subroutine) for each other component in the engine, including the pump inlet line, the pump discharge line, the turbine inlet line heat exchanger, the diluent orifice, and the turbine power control valve.

The basic method of solution has been the computation of a series of equations written assuming equilibrium energy balances within the system. Thus, in most cases, system parameters have been assumed and the related system energies computed. If conservation of energy has not been maintained, as it normally would not be for the first parameter assumptions, new values of the system parameters are assumed and a new calculation of system energy balances is obtained. This iteration process then continues until the system energies agree within the limits set by the input computational tolerances. The methods used for obtaining new values of system parameters for successive iterations are different in different parts of the program because of different stability problems, but the basic process is the same. Thus, the basic solution method used in the program is the solution of the equations of conservation of energy and continuity of mass flow.

In general, an incremental calculational technique has been used for the heat-transfer and fluid-flow calculations. Thus, the inlet conditions

of temperature, pressure, and flow rate to any computational increment are assumed to be known and to hold constant over the length of the computational increment. Heat-transfer calculations are then performed to obtain the temperature distribution in the solid materials. In the Nuclear Engine Analysis Program, the temperature calculations are performed by Subroutines TOZZ1 (for the nozzle) and by Subroutines TUBE1 and TUBE3 (for the reflector, shield, and core). The derivation of the heat-transfer equations of TUBE1 will be given as an example of the heat-transfer calculations performed throughout the program.

The differential equation for steady-state heat transfer in a thick-walled cylinder with internal heat generation is (Reference 1),

$$\frac{d^2T}{dr^2} + \frac{1}{r}\frac{dT}{dr} = -\frac{q'''}{k}$$

where

T = temperature at any radius, r, °R

r = radius from centerline of cylinder, in.

q''' = internal heat generation rate, Btu/in.^{3}-sec

k = thermal conductivity, Btu/in.-sec-°R

Rearranging and solving,

$$r\frac{d^2T}{dr^2} + \frac{dT}{dr} = -\frac{q'''}{k} r$$

$$\frac{d}{dr}\left(r\frac{dT}{dr}\right) = -\frac{q'''}{k} r$$

$$r\frac{dT}{dr} = -q'''\frac{r^2}{2k} + C$$

$$\frac{dT}{dr} = -\left(\frac{q'''}{k}\right)\left(\frac{r}{2}\right) + \frac{C}{r}$$

$$T_M - T_W = -\left(\frac{q'''}{k}\right)\left(\frac{r_o^2 - r_i^2}{4}\right) + C \ln\frac{r_o}{r_i}$$

where

T_M = maximum material temperature, ^{o}R

T_W = coolant channel wall temperature, ^{o}R

r_o = cylinder outer radius, in.

r_i = cylinder inner radius, in.

Since the outer surface of the cylinder is assumed to be adiabatic,

$$\frac{dT}{dr} = 0, \text{ at } r = r_o$$

Thus

$$\frac{dT}{dr} = -\left(\frac{q'''}{k}\right)\left(\frac{r_o}{2}\right) + \frac{C}{r_o} = 0$$

$$C = \left(\frac{q'''}{k}\right)\left(\frac{r_o^{\,2}}{2}\right)$$

and,

$$T_M = T_W + \frac{q'''}{k}\left[\frac{r_o^{\,2}}{2}\ln\left(\frac{r_o}{r_i}\right) - \frac{r_o^{\,2} - r_i^{\,2}}{4}\right]$$

To solve for the wall temperature, T_W, the heat flux on the coolant side of the wall is equated with the heat flux on the solid material side of the wall, which is, of course, equal to the heat generated internally in the solid material.

$$q_c'' = 2\pi r_i \,\Delta\ell\, h \;(T_W - T_B)$$

$$q_s'' = q''' \pi \,(r_o^{\,2} - r_i^{\,2})\,\Delta\ell$$

where

q_c' = coolant-side heat flux, Btu/sec

q_s'' = solid-material-side heat flux, Btu/sec

$\Delta\ell$ = incremental length, in.

h = convective heat-transfer coefficient, Btu/in.^{2}-sec-^{o}R

Equating the two heat fluxes,

$$2\pi r_i \,\Delta\ell\, h\,(T_W - T_B) = q''' \pi\,(r_c^{\,2} - r_i^{\,2})\,\Delta\ell$$

and,

$$T_W = T_B + \frac{q'''}{h}\left[\frac{r_o^{\,2} - r_i^{\,2}}{2\, r_i}\right]$$

The final thermal calculation is the heat transfer, q''_c or q''_s, from the solid material to the fluid. By assuming that the heat-transfer and temperature distribution holds over the entire length of the computational increment, the energy input to the fluid may be obtained. The momentum and en[illegible] equations for the fluid are then solved to obtain the fluid pressure and tempe[illegible] ture leaving the computational increment. These fluid calculations are performe[illegible] in Subroutine CHANGE, the derivation of the equations of which is given below.

For steady-flow of a fluid, when gravitational effects are negligible and no work is done by the fluid, the energy equation may be written in the following difference form (Reference 2):

$$\Delta h + \Delta\left(\frac{W\,V^2}{2\,Jg_c}\right) = Q$$

where

Δh = change in enthalpy of fluid of mass, W, Btu/sec

W = mass flow rate of fluid, lbm/sec

V = bulk fluid velocity, in./sec

J = mechanical equivalent of heat, 9338 in.-lbf/Btu

g_c = gravitational constant, 386 lbm-in./lbf-sec^2

Q = energy in the form of heat added to fluid, Btu/sec

Then,

$$\frac{\Delta h}{W} = \frac{Q}{W} - \frac{\Delta V^2}{2\,g_c J}$$

Since,

$$V^2 = \frac{W^2}{A^2 \rho^2}$$

where

A = flow area, in.^{2}

ρ = fluid density, lbm/in.

$$\frac{\Delta h}{W} = \frac{Q}{W} - \frac{W^2}{2 g_c J} \Delta \left(\frac{1}{A\rho} \right)^2$$

Letting $\Delta H = \frac{\Delta h}{W}$ = change in enthalpy of fluid (in Btu/lbm), and subscripts 1 and 2 represent entrance and exit conditions, respectively, the energy equation may be written in the form

$$\Delta H = \frac{Q}{W} - \frac{W^2}{2 g_c J} \left[\frac{1}{(A_2 \rho_2)^2} - \frac{1}{(A_1 \rho_1)^2} \right]$$

To derive the momentum equation, neglecting gravitational and work terms, for steady flow in a coolant passage of varying area, a force balance may be made by referring to Figure 3. The force balance is

$$P_1 A_1 + \frac{1}{\alpha g_c} \left(\rho_1 V_1^2 \right) A_1 + P_{avg} \left(A_2 - A_1 \right)$$

$$= P_2 A_2 + \frac{1}{\alpha g_c} \left(\rho_2 V_2^2 \right) A_2 + P_f A_2$$

where

P = static pressure of fluid, lbf/in.^{2}

V = average fluid velocity, in./sec

ρ = fluid density, lbm/in.^{3}

A = flow area, in.^{2}

P_f = frictional pressure, lbf/in.^{2}

P_{avg} = average of inlet and exit static pressures, lbf/in.^{2}

g_c = gravitational constant, 386 lbm-in./lbf-sec^2

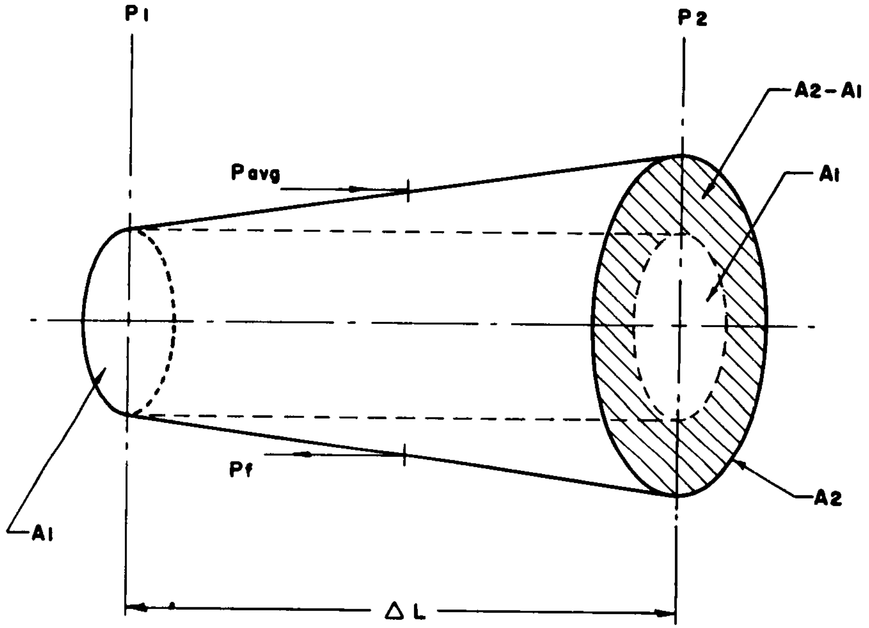

Figure 3

Fluid Element

$$\alpha = \begin{cases} 1, & \text{for laminar flow in circular tubes} \\ 2, & \text{for turbulent flow in circular tubes} \end{cases}$$

Subscripts 1 and 2 refer to inlet and exit conditions, respectively.

Since

$$F_{avg} = \frac{P_1 + P_2}{2}$$

by rearranging, the following relationship can be obtained:

$$P_1 \left(A_1 + \frac{A_2}{2} - \frac{A_1}{2} \right) - P_2 \left(A_2 - \frac{A_2}{2} + \frac{A_1}{2} \right)$$

$$= \frac{1}{\alpha g_c} \left(A_2 \rho_2 V_2^2 - A_1 \rho_1 V_1^2 \right) + P_f A_2$$

Then

$$\left(P_1 - P_2 \right) \left(\frac{A_1 + A_2}{2} \right) = \frac{1}{\alpha g_c} \left(A_2 \rho_2 V_2^2 - A_1 \rho_1 V_1^2 \right) + P_f A_2$$

Since

$$\Delta P = P_1 - P_2$$

$$P_f = \frac{f \rho_1 V_1^2}{2 g_c d_h} \Delta \ell$$

$$V = \frac{W}{\rho A}$$

where

f = Blasius friction factor
$\Delta \ell$ = length of increment, in.
$\dot{W}$ = mass flow rate, lbm/sec
d_h = hydraulic diameter, in.
ΔP = pressure drop over increment, lbf/in.^{2}

Then

$$\Delta P = \frac{2}{A_1 + A_2} \left[\frac{f \Delta \ell W^2 A_2}{2 g_c d_h A_1^2 \rho_1} + \frac{W^2}{\alpha g_c} \left(\frac{1}{A_2 \rho_2} - \frac{1}{A_1 \rho_1} \right) \right]$$

$$= \frac{2 A_2}{A_1 + A_2} \frac{W^2}{g_c} \left[\frac{f \Delta \ell}{2 d_h A_1^2 \rho_1} + \frac{1}{\alpha} \left(\frac{1}{A_2^2 \rho_2} - \frac{1}{A_2 A_1 \rho_1} \right) \right]$$

The basic computation for the turbopump loop is the determination of the turbine flow rate necessary to supply the required pump power. Conditions in the rest of the system, including the pump flow rate and pump discharge pressure, are held constant during the computation of the turbopump loop. Thus, it is possible to compute the required pump power and, in turn, the required turbine power and flow rate.

$$\text{Pump power} = \frac{W_1 \Delta H_p}{\epsilon_p}$$

$$\text{Turbine power} = W_{18} H_{18} J \epsilon_T \left[1 - \left(\frac{P_{19}}{P_{18}} \right)^{\frac{\gamma - 1}{\gamma}} \right]$$

where

W_1 = pump flow rate, lbm/sec
W_{18} = turbine flow rate, lbm/sec
ΔH_p = head rise across pump, in.
ϵ_p = pump efficiency
ϵ_T = turbine efficiency
H_{18} = turbine inlet enthalpy, Btu/lbm
J = mechanical equivalent of heat, 9338 in.-lbf/Btu
P_{19} = turbine exhaust pressure, lbf/in.^{2}
P_{18} = turbine inlet pressure, lbf/in.^{2}
γ = specific heat ratio

Equating the two powers and solving,

$$W_{18} = \frac{W_1 \, \Delta H_p}{H_{18} \, J \, \epsilon_p \, \epsilon_T \left[1 - \left(\frac{P_{19}}{P_{18}} \right)^{\frac{\gamma - 1}{\gamma}} \right]}$$

But, assuming perfect mixing of the hot bleed and diluent fluids, the turbine inlet enthalpy is

$$H_{18} = \frac{(W_{18} - W_{16}) \, H_c + W_{16} \, H_{15}}{W_{18}}$$

where

W_{16} = diluent flow rate, lbm/sec

H_c = hot bleed enthalpy, Btu/lbm

H_{15} = diluent enthalpy, Btu/lbm

Substituting and solving for W_{18}

$$W_{18} = \frac{W_1 \, \Delta H_p}{J \, \epsilon_p \, \epsilon_T \left[1 - \left(\frac{P_{19}}{P_{18}} \right)^{\frac{\gamma - 1}{\gamma}} \right]} + \frac{W_{16} \, (H_c - H_{15})}{H_c}$$

To solve this equation, it is necessary to know the turbine and pump efficiencies. However, since these figures depend on other parameters - including turbopump speed - it is necessary to assume initial values and iterate towards a solution. Also, the exact temperature and pressure at the turbine inlet is a function of the turbine inlet line heat-exchanger calculations which, therefore, must be part of the turbopump iteration.

The solution of the previous equations relies on heat-transfer and friction-factor correlations, turbopump data, and hydrogen-properties data which are computed as a part of the overall program. A large part of the program consists of hydrogen-properties subroutines which provide a complete representation of the thermodynamic and transport properties of hydrogen. The heat-transfer correlations, friction factor correlations, and turbopump data, however, may be changed at any time that newer correlations become available, since they are used simply to obtain values for the basic program computations.

Finally, when all other parts of the program have converged, the program computes several significant system performance characteristics including engine thrust, specific impulse, turbine power control valve position, and reactor power level. These quantities are obtained explicitly from equations once all other system parameters have been computed.

C. PROGRAM LOGIC

The NERVA Hot-Bleed Engine described in the preceding section is analyzed by inputting the system geometry and component characteristics, and a demanded chamber pressure and chamber temperature. The digital computer program then solves a series of system energy balance equations to converge on the system parameters which are consistent with these system inputs and demanded chamber conditions.

By referring to Figure 4, the program computational logic may be explained. The program is divided into three chains, since the overall size of the program is much greater than the number of memory locations available in the machine. Thus, while any one chain is in the machine, the other two chains are stored on tape, and must be read into the machine when it is necessary to transfer to that part of the program.

The exact splitting of various parts of the program between the three chains has been done for programing reasons and has no particular engineering significance. Chain 1 sets up the program solution by loading various properties data and transferring control to Chain 2. Chain 2 loads the input data, consisting of a complete engine system description and the demanded chamber pressure and temperature.

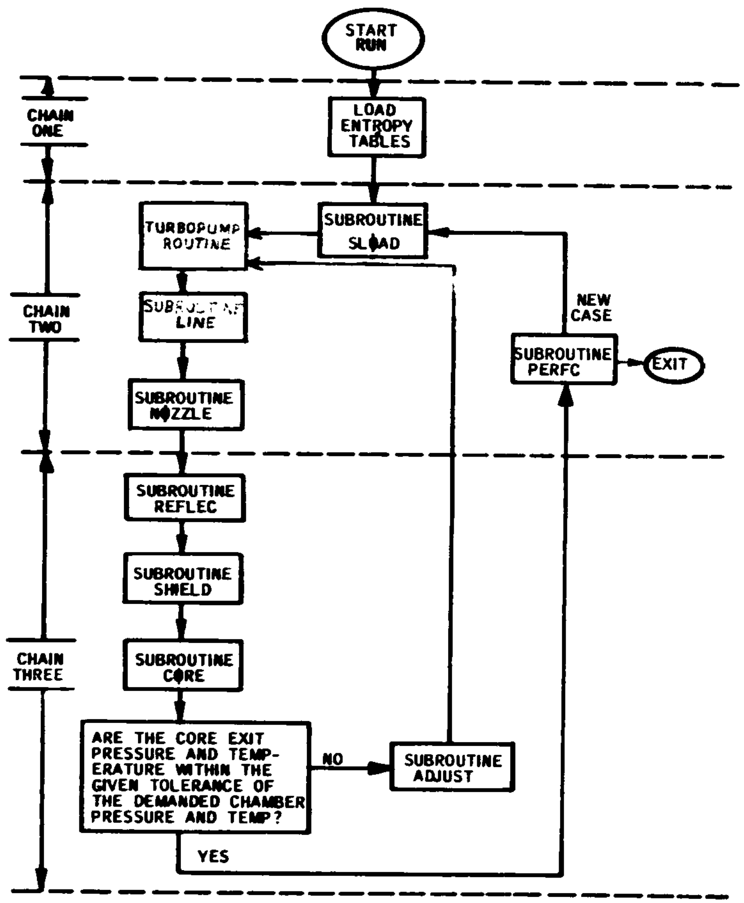

Figure 4

Program Flow Diagram

The first step in the calculational procedure is to use the demanded chamber pressure and temperature to calculate the nozzle mass flow rate. Then, approximate equations are used to calculate initial guesses for the pump discharge pressure, reactor power level, and pump flow rate. The pump inlet pressure and flow rate are then determined, thus providing the pump inlet conditions. The required pump power is then computed and, from this, the turbopump speed, the pump efficiency, the pump specific speed and thus the required turbine energy are computed. For an assumed turbine efficiency, the turbine flow rate (and thus the hot bleed flow rate) is computed. The turbine inlet temperature and pressure are then computed and the turbine efficiency read from an input curve. If this turbine efficiency is not equal to the assumed turbine efficiency, the turbine flow rate, inlet temperature, and efficiency will be recomputed. This iteration process continues until the computed turbine efficiency is the same as the assumed turbine efficiency. The heat exchange between the turbine flow and the diluent flow and the pressure drop in the diluent and turbine inlet lines are computed to determine the diluent orifice inlet temperature and pressure. The diluent flow rate is then recomputed for the newly computed temperature and pressure. If the difference between the new diluent flow rate and the previously estimated diluent flow rate is not within the required tolerance, a new diluent flow rate is estimated and is used to recompute the required pump power. All operations are then repeated until a newly computed diluent flow rate agrees with the previously computed flow.

The program then calls Subroutine LINE. Using the computed pump flow rate and the estimated pump discharge pressure, the pressure drop and temperature change in the pump discharge line are computed in this subroutine. The pressure and temperature leaving the pump discharge line are thus obtained.

Next, the program calls Subroutine NOZZLE, which computes the propellant temperatures and pressures and the wall temperatures in the nozzle coolant tubes. In addition, if a skirt or bolt coolant line is used in parallel with the nozzle, the flow distribution between the nozzle and skirt is calculated and the propellant temperatures and pressures and the wall temperatures in the skirt are determined. Both radiant heat transfer from the reactor core and convective heat transfer from the nozzle exhaust gases are included in the calculations. The nozzle exit pressure and temperature are thus determined.

At this point, the program transfers to Chain 3. The program then calls Subroutine REFLEC, where the nozzle exit conditions are used as inlet conditions for the reflector calculations. The heat transfer and pressure drop are computed for each type of reflector flow channel, using an assumed flow distribution. If the pressure drops through all channels are not the same, the flow is redistributed and the pressure drop and heat-transfer calculations are repeated until the pressure drops are all equal. The reflector exit temperature and pressure are then computed.

Returning to the main program, the tank pressurization bleed flow rate and the diluent flow rate are subtracted from the reflector flow rate to obtain the shield flow rate. This assumes that the option for extraction of the diluent flow from the shield inlet plenum is used. If one of the other options had been used, the diluent flow would have been extracted either from the nozzle inlet plenum or the nozzle exit plenum.

The program then calls Subroutine SHIELD where the reflector exit conditions are used as inlet conditions to the shield. Heat transfer, pressure drop, and flow distribution calculations are then performed that are analogous to those in the reflector to obtain the shield exit pressure and temperature.

The program then calls Subroutine CORE, using the shield exit conditions as inlet conditions. In the reactor core, there may be tie rod channels in parallel with the fuel element channels. Heat transfer, pressure drop, and flow distribution calculations are performed for the fuel element channels and, if necessary, for the tie-rod channels. The propellant temperatures and pressures and the material temperatures are obtained for both the fuel elements and the tie rods in the reactor core. A reactor core exit temperature and pressure are thus obtained.

In the main program, the core exit pressure and temperature just calculated are compared with the input demanded chamber pressure and temperature. If the difference between either pair of calculated and demanded parameters is

greater than input tolerance values, the program calls Subroutine ADJUST. Subroutine ADJUST uses the last computed values of pump discharge pressure and reactor power to compute new guesses at the pump discharge pressure and reactor power. The program then returns to Chain 2 where the system calculations are repeated, beginning with the turbopump routine.

If there is agreement between the calculated and demanded values of chamber pressure and temperature, the program transfers to Chain 2 and calls Subroutine PERFC. In this subroutine, the parameters associated with the system performance are computed. These characteristics include the thrust, specific impulse, turbine power control valve position, and total nuclear power level. The program then prints its output and either (1) transfers back to the beginning of Chain 2 to start a new problem, or (2) stops.

III. ROUTINES AND SUBROUTINES

The following section contains a complete listing of the routines and subroutines used in the Nuclear Engine Analysis Program and a description of their functions, logical arrangement, the equations used for solution, and the analytical assumptions. More detailed information on the routines and subroutines and their operation can be obtained by reference to Appendix C, which contains the complete Fortran listings, and to Appendix D, which contains complete flow charts. Any nomenclature used in the following section is either defined immediately following the equations, or is given in Appendix A.

A. TURBOPUMP ROUTINE

1. Description

The Turbopump Routine is assumed to consist of those calculations of Chain 2 which are not performed in subroutines. These calculations include making first guesses for starting the program computations and analyzing the pump inlet line, the turbopump assembly, and the turbine inlet line heat exchanger. The logical arrangement of this routine and its relationship to the rest of Chain 2 may be seen by referring to Figure 5. There are three ways to enter Chain 2: from Chain 1 at the beginning of the program, from Chain 3 when the program has not converged, and from Chain 3 when the program has converged. When Chain 2 is entered from Chain 3 when the program has converged, Subroutine PERFC is called and, on return, the program stops or goes to the next case. When Chain 2 is entered from Chain 1, Subroutine SLOAD is immediately called to read the program input data. Then, from the input demand chamber pressure and temperature and the nozzle dimensions, the nozzle flow rate is computed.

Empirical equations, using input constants, are used to make guesses of initial values for the pump discharge pressure and pump flow rate. Other empirical equations are used to make guesses of the diluent orifice pressure, temperature, and flow rate. Next, using the parameters obtained so far, the pump inlet pressure and temperature and the net positive suction pressure are calculated. It is at these calculations that Chain 2 is entered from Chain 3 when the program has not converged and the iteration process is to be continued. Following this, the pump parameters - including capacity, head rise, speed, efficiency, specific speed, and power - are computed.

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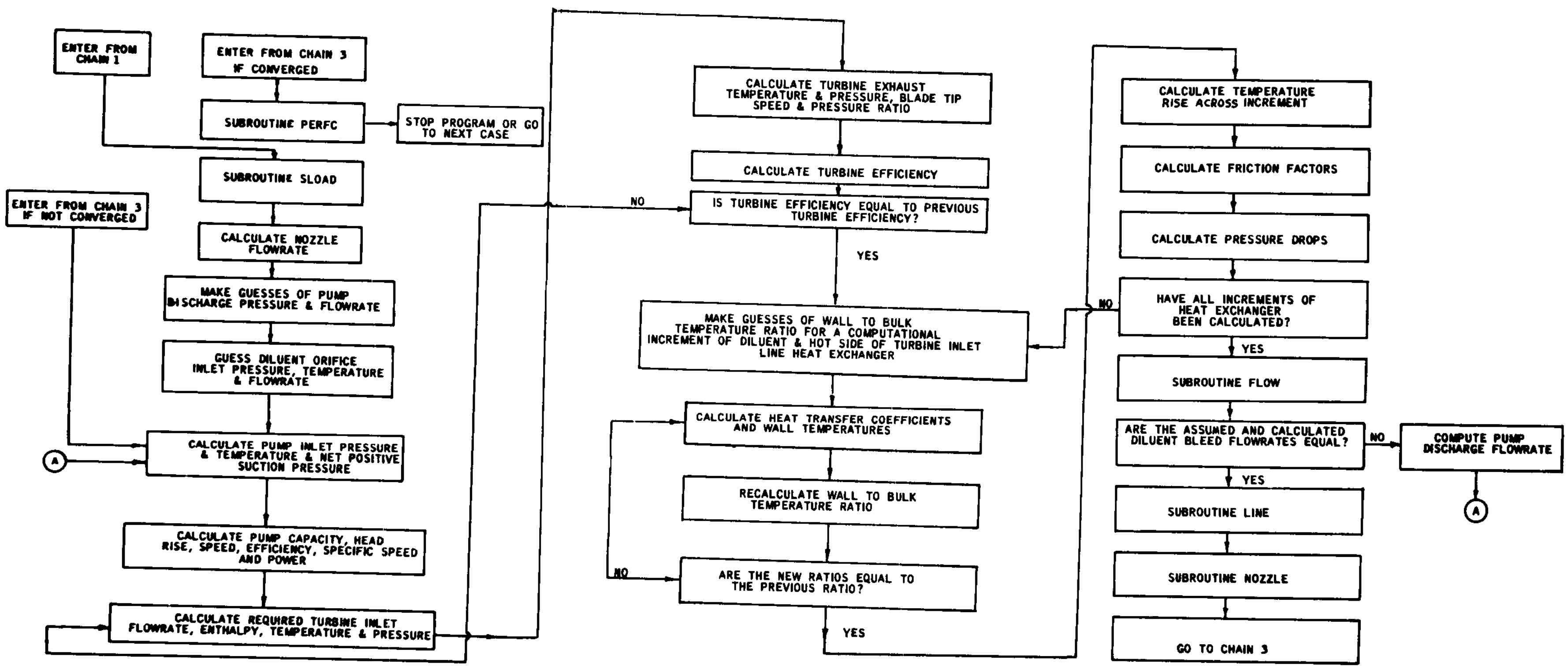

Figure 5

Chain 2 Flow Diagram

The turbopump shaft speed is computed either by equations or by Subroutine CURVE, depending on which of several optional pumps is called for. Then the key calculations of the Turbopump Routine are performed. These are the calculations of the turbine flow rate necessary to supply the required turbopump power for the assumed diluent conditions, and of the turbine inlet enthalpy, temperature, and pressure. The turbine exhaust temperature and pressure, the turbine blade tip speed, and the turbine pressure ratio are determined. From these values, the turbine efficiency is calculated. If the computed turbine efficiency is not equal to the previous value of turbine efficiency (the first guess having been obtained from an input value), the program goes back to the first turbine calculation and begins another iteration. When the turbine efficiency has converged, the program begins the turbine inlet line heat exchanger calculations. First, the wall to bulk temperature ratios for each side of the heat exchanger are assumed. Then, the heat-transfer coefficients are calculated and the duct wall temperatures are determined. The wall to bulk temperature ratios are then recomputed and compared with the previous values. If they do not agree, the heat-transfer coefficients and wall temperatures are recomputed. If they do agree, the heat transfer to the diluent from the turbine inlet flow is computed and the fluid temperature change across an increment is determined.

The friction factors and the pressure drops are then determined. The heat transfer and fluid flow calculations are repeated for each increment of the heat exchanger. Using the new values for the temperature and pressure at the diluent orifice, Subroutine FLOW is called to compute the diluent flow rate. If the newly calculated value of the diluent flow rate does not agree with the previous value, the pump discharge flow rate is recomputed and the program begins another iteration of the Turbopump Routine. If the two values of diluent flow rate agree, the program continues by calling Subroutine LINE and Subroutine NOZZLE, followed by transfer to Chain 3.

2. **Equations**

The equations involved in the Turbopump Routine are given below.

$$WD11 = C11A11 \frac{PC}{\sqrt{TC}}$$

$$PZ - P1 = C1P1 \frac{(WD1)^2}{\rho_1}$$

$$ETAP = -2.44 \left(\frac{Q1}{N}\right)^2 + 2.01 \frac{Q1}{N} + 0.286 \text{ (for MK III MOD IV TPA)}$$

$$POWER = 12 \frac{(WD1)\ (H1D2)}{(ETAP)}$$

$$ETGAM = ET^* \left[1 - (P19/P18)^{\frac{\gamma-1}{\gamma}}\right]$$

$$WD18 = (POWER)/(J^*ETGAM) + WD16^*(HC-H15)/HC$$

$$H18 = \frac{(WD18 - WD16)\ (HC) + (WD16)\ (H15)}{WD18}$$

$$P18 = \frac{(WD18)\sqrt{T18}}{C18}$$

If $\frac{PA}{P19} < 0.528$, $P19 = (WD18)(\sqrt{T19})\ (C19)$

If $\frac{PA}{P19} > 0.528$, $P19 = (WD18)(\sqrt{T19})\ (K)$

where k is a function of the pressure ratio $\left(\frac{P19}{PA}\right)$; i.e., the subsonic, isentropic flow equation

$$WD19 = A19 \sqrt{\left(\frac{2g\gamma}{\gamma - 1}\right) (P19)\ P19 \left[\left(\frac{PA}{P19}\right)^{2/\gamma} - \left(\frac{PA}{P19}\right)^{\frac{\gamma+1}{\gamma}}\right]}$$

$$C_o = \sqrt{2g\ JC_pT_{18} \left[1 - \left(\frac{P19}{P18}\right)^{\frac{\gamma-1}{\gamma}}\right]}$$

$$U = C18P2\ (N)$$

$$ET = C18P5\left(\frac{U}{CO}\right)^3 + C18P6\left(\frac{U}{CO}\right)^2 + C18P7\left(\frac{U}{CO}\right)$$

$$HB15 = 0.028\,\frac{1}{(DH15)^{0.2}}\left(\frac{WD16}{A15}\right)^{0.8}\left[\frac{K\,P_r^{0.4}}{\mu^{0.8}}\right]\left[\frac{T15}{TW15}\right]^{0.64}$$

$$HB17 = 0.021\,\frac{1}{(DH)^{0.2}}\left(\frac{4\,WD17}{\pi}\right)^{0.8}\left[\frac{K\,P_r^{0.33}}{\mu^{0.8}}\right]\left[\frac{T17}{TW17}\right]^{0.15}$$

$$QDDT = \pi\,\frac{(D)\ (DELTL)\ (T17 - T15)}{\frac{TW}{K_w} + \frac{1}{HB15} + \frac{1}{HB17}}$$

$$FF = \left(\frac{1}{2\log\left(Re\sqrt{FF}\right) - 0.80}\right)^2$$

where FF = friction factor

Re = Reynold's number

3. <u>Assumptions</u>

a. The main nozzle flow rate is calculated assuming sonic isentropic flow with a constant specific heat ratio.

b. The pump inlet line pressure drop is computed using a constant pressure loss coefficient and a constant density.

c. The pump head rise and volume flow rate are based on the density at the pump inlet.

d. Pump speed vs capacity data are contained in Subroutine CURVE as tabular data obtained from Reference 3. These data are not valid below the point of pump instability. The pump efficiency data are obtained from the same source.

e. The turbine inlet enthalpy is a weighted average of the thrust chamber and diluent enthalpies.

f. The turbine inlet nozzle has sonic isentropic flow with a constant specific heat ratio.

g. The properties evaluations for the turbine inlet line heat exchanger are based on the inlet conditions to each computational increment.

h. Turbulent flow is assumed in the turbine inlet line heat exchanger.

i. There is isothermal expansion across the turbine power control valve.

j. The kinetic energy of the fluid is negligible in the turbine inlet line heat exchanger fluid flow calculation.

k. There may be any number, NPRM, of turbine inlet line heat exchanger computational increments of length, DELTL.

l. For the diluent side of the turbine inlet line heat exchanger, the heat transfer coefficient, HB15, is computed from the Thompson "A" heat-transfer correlation.

m. For the hot gas side of the turbine inlet line heat exchanger, the heat transfer coefficient, HB17, is computed from a modified Sider-Tate heat-transfer correlation.

n. Thermal conductivity in the turbine inlet line heat exchanger wall is based on the arithmetic mean of the diluent and hot-gas side wall temperatures.

o. The friction factor, FF, is calculated from a modified Nikuradse friction factor equation.

B. SUBROUTINE ADJUST

1. <u>Description</u>

If the core exit temperature and pressure are not within a given tolerance of the input demand chamber pressure and temperature, the program has not converged and Chain 3 calls for Subroutine ADJUST. The subroutine adjusts the pump discharge pressure, P2, and reactor power level, QF, by the following formulas (Reference 7) so that the demand chamber conditions may be more closely met in the next iteration.

2. **Equations**

First iteration

$$P2_{new} = PC - P9 + P2$$

$$QF_{new} = \frac{QF* \left[(WD9* (HC - H5) + WD21* (H6 - H5)\right]}{WD9* (H9 - H5) + WD21* (H6 - H5)}$$

Succeeding iterations are as follows:

$$P2_{new} = PC + \Delta P_{new}$$

$$\Delta P_{new} = \Delta P_n \left(\frac{\Delta P_{n+1} - \Delta P_n}{\Delta P_n - \Delta P_{n-1}}\right) + \Delta P_{n+1} \left(1 - \frac{\Delta P_{n+1} - \Delta P_n}{\Delta P_n - \Delta P_{n-1}}\right)$$

where

$$\Delta P = P2 - P9$$

and

$$\phi_{F_{new}} = \phi_{F_n} \left(\frac{\phi_{F_{n+1}} - \phi_{F_n}}{\phi_{F_n} - \phi_{F_{n-1}}}\right) + \phi_{F_{n+1}} \left(1 - \frac{\phi_{F_{n+1}} - \phi_{F_n}}{\phi_{F_n} - \phi_{F_{n-1}}}\right)$$

where

$$\phi_{F_1} = \frac{\phi_F * \left[(WD9* (HC - H5) + WD21* (H6 - H5)\right]}{WD9* (H9 - H5) + WD21* (H6 - H5)}$$

where subscripts, n+1, n, and n-1 refer to succeeding program iterations.

C. SUBROUTINE CHANGE

1. **Description**

Subroutine CHANGE is called by Subroutines COOLX, SKIRT, REFLEC, SHIELD, and CORE. It provides a generalized difference solution of the momentum and energy equations for fluid flow in an increment, I. Given the channel geometry,

inlet temperature, pressure and flow rate, and the heat input rate for a particular increment (I), this subroutine obtains the exit temperature and pressure by a simultaneous solution of the momentum and energy equations. Included in the subroutine are expressions for the friction factor for each range of Reynold's number. The equations include the effect of area change over the length of the increment. The basic assumption in the subroutine is that the length of each increment will be made small enough that holding properties constant over the increment will result in only a very small error in exit temperature and pressure.

2. **Equations**

The equations involved in Subroutine CHANGE are given below.

$$\Delta P = \frac{2A_2}{(A_2 + A_1)} \frac{W^2}{g_c} \left[\frac{FF(DL)}{2\, d_h} \frac{1}{A_1^{\,2}\, \rho_1} + \frac{1}{2} \frac{1}{A_2^{\,2}\, \rho_2} - \frac{1}{A_2\, A_1\, \rho_1}\right]$$

If Re < 1200, $FF = \frac{64}{Re}$

If 1200 < Re < 2 x 10^5, $FF = \frac{0.316}{Re^{0.25}}$

If Re > 2 x 10^5, $FF = \frac{0.106}{Re^{0.161}}$

$$T_f = 0.4\, T_w + 0.6\, T_b$$

$$\Delta H = \frac{Q}{W} - \frac{W^2}{2\, g_c J} \left[\left(\frac{1}{A_2\, \rho_2}\right)^2 - \left(\frac{1}{A_1\, \rho_1}\right)^2\right]$$

where

ΔH = enthalpy change per computational increment, Btu/lbm

Q = heat input per computational increment, Btu/sec

$\dot{w}$ = flow rate, lbm/sec

g_c = gravitational constant = 386 lbm-in./lbf-sec^2

J = mechanical equivalent of heat = 9338 in.-lbf/Btu

A_1 = flow area at inlet of increment, in.^{2}

ρ_1 = density at inlet of increment, lbm/in.^{3}

A_2 = area at exit of increment, in.^{2}

ρ_2 = density at exit of increment, lbm/in.^{3}

Re = Reynolds number in which the viscosity is evaluated at the film temperature, T_f

ΔP = pressure drop, psi

FF = friction factor

d_h = hydraulic diameter, in.

DL = increment length, in.

T_f = film temperature, ^oR

T_w = wall temperature, ^oR

T_b = bulk fluid temperature, ^oR

3. Assumptions

a. The fluid transport properties are evaluated at the inlet to each computational increment, I, and are assumed constant over the increment.

b. There is subsonic flow.

c. The gravitational force term in the momentum equation is negligible.

d. The frictional work and potential energy terms in the energy equation are negligible.

e. The friction factor, FF, is evaluated at the film temperature, T_f.

D. SUBROUTINE COOLX

1. Description

Subroutine COOLX, which is called by Subroutine NOZZLE, performs the thermal and fluid dynamic computations for the nozzle. The logical arrangement of this subroutine is shown in Figure 6. The subroutine first calculates the nozzle entrance pressure drop. The subroutine then begins a DØ loop where, for each increment, it calls, in succession, Subroutine POW to

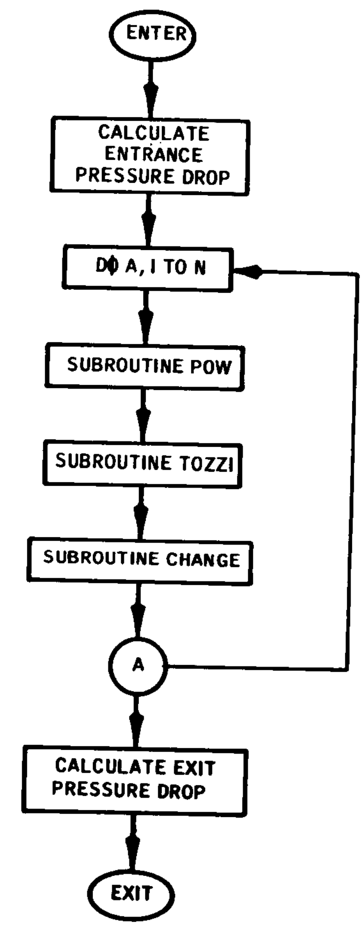

Figure 6

Subroutine COOLX and SKIRT Flow Diagram

obtain the nuclear heat generation rate, Subroutine TOZZl to perform the thermal calculations, and Subroutine CHANGE to solve the energy and momentum equations. After the last increment, the exit pressure drop is calculated and the program returns to Subroutine NOZZLE.

2. Equations

The equations involved in Subroutine COOLX are given below.

$$DELPE = \frac{XKTE * (WD3N)^2}{2\ g\ \rho * (AME)^2}$$

$$DELPX = \frac{XKTX * (WD3N)^2}{2\ g\ \rho * (AMX)^2}$$

where

DELPE = nozzle entrance pressure drop, psi

DELPX = nozzle exit pressure drop, psi

g = gravitational constant, in./sec^2

ρ = fluid density, lbm/in.^{3}

3. Assumptions

a. The nozzle is divided into 10 axial increments of arbitrary length.

b. Entrance and exit pressure losses are computed using constant pressure loss coefficients.

c. There is single pass flow from the highest expansion ratio of the nozzle to the highest contraction ratio.

E. SUBROUTINE CORE

1. Description

Subroutine CORE, which is called by Chain 3, sets up the reactor core fuel element thermal and fluid flow computations, performs the thermal computations and sets up the fluid flow computations for the reactor core tie rods, and balances the flow rates among all reactor core flow channels.

The logical arrangement of this subroutine may be seen by referring to Figure 7. Subroutine CORE first assumes flow rates for each type of fuel element and tie-rod flow channel in the reactor core. There may be from one to five types of fuel element flow channels and from zero to three types of tie-rod flow channels. The subroutine begins a DØ loop to sequentially compute each type of fuel element flow channel. First, the entrance pressure drop is calculated. The subroutine then begins a DØ loop, where for each increment it calls, in succession, Subroutine POW to obtain the nuclear heat generation rate, Subroutine TUBEl to perform the thermal calculations, and Subroutine CHANGE to solve the momentum and energy equations. Next, the exit pressure drop is calculated and the subroutine continues in the DØ loop to calculate the next type of fuel element flow channel. After all types of fuel element flow channels have been calculated, the subroutine begins the tie-rod calculations or, if there are no tie rods, proceeds directly to the convergence tests.

The tie-rod channels are assumed to consist of a cylindrical tie rod surrounded by a flow channel of annular cross section, whose outer surface is formed by the tie-rod module. The tie-rod module may be divided into as many as 15 concentric annular segments. For each type of tie-rod flow channel, the subroutine first computes several geometric parameters. The subroutine then begins a DØ loop to sequentially compute each type of tie-rod flow channel. First, the entrance pressure drop is calculated. The subroutine then begins a DØ loop to perform the thermal and fluid flow calculations in sequence for each computational increment. The fluid heat transfer coefficient is computed; then Subroutine POW is called to compute the nuclear heat generation rate. With a guess having been made of the heat flux into the fluid, the temperature at each radial annular segment is computed from the heat flux across that boundary and the thermal conductance of that segment. If the temperature of the outer boundary is not equal to the maximum temperature of the adjacent fuel element channel, and therefore the heat flux at the boundary is not zero, the assumed heat flux into the fluid is changed using the error equation given below and the iteration is continued.

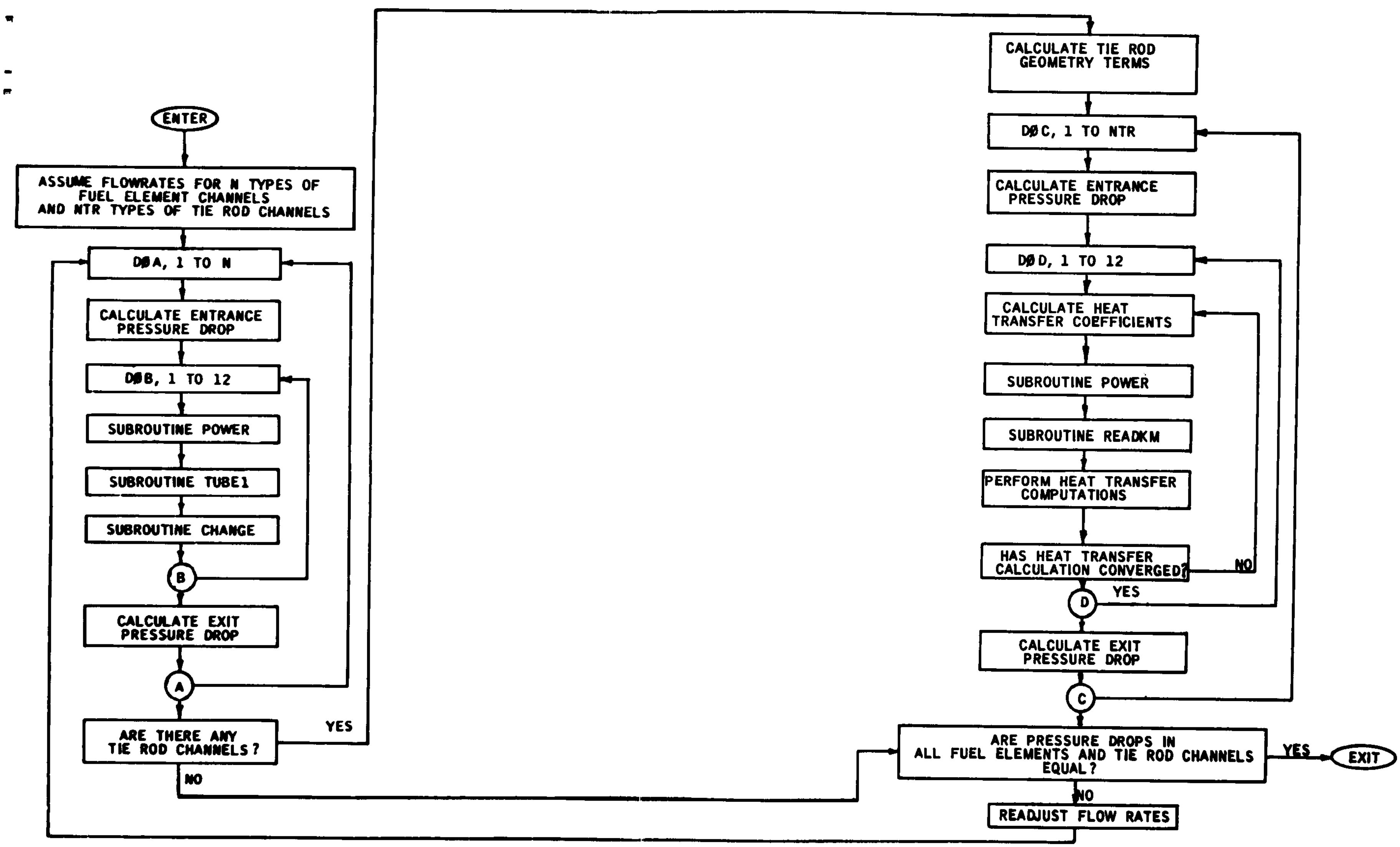

Figure 7

Subroutine CORE Flow Diagram

When the temperatures have converged, Subroutine CHANGE is called to solve the momentum and energy equations. When the last computational increment has been computed, the exit pressure drop is calculated and the subroutine continues in the DØ loop to calculate the next type of tie-rod flow channel. After all types of tie-rod flow channels have been calculated (or if there are no tie-rod channels, following the fuel element calculations) the subroutine compares the pressure drops for all types of channels. If all of the pressure drops are equal, the subroutine has converged and so returns to the main program. If they are not all equal, the subroutine has not converged, so the flow rates are readjusted, using the equation given below, and another iteration is performed. The flow adjustment equations are derived assuming that the pressure drops are proportional to the square of the flow rates, an assumption which is close enough to being valid that convergence is very sure and rapid.

2. **Equations**

The equations involved in Subroutine CORE are given below.

$$\mathrm{DELPE}(J) = \mathrm{KTE}(J)\,\frac{1}{2\,g_c}\left[\frac{W(J)}{A(J)}\right]^2 \frac{1}{\rho_E}$$

$$\mathrm{DELPX}(J) = \mathrm{KTX}(J)\,\frac{1}{2\,g_c}\left[\frac{W(J)}{A(J)}\right]^2 \frac{1}{\rho_X}$$

$$T_{k+1} = T_k + \left[\frac{\frac{q_k + qA\,\Delta L}{2}}{U}\right]$$

$$A = \pi\,(R_{k+1} + R_k)\,\Delta L$$

For convection

$$U = hA$$

For conduction

$$U = \frac{\ln \frac{R_{k+1}}{R_k}}{2\pi\,K\,\Delta L}$$

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For contact conductance

$$U = UTR$$

$$T_M = T_W + q''' \frac{TR\ RT^2}{4\ K_{TR}}$$

$$T_W = T_b + \frac{q'''\ TR\ RT}{2h}$$

$$SUM = \sum_{J=1}^{N+NTR} DP(J)$$

$$DBP = \frac{SUM}{N}$$ [Note: If the largest DP(J) is more than twice DBP, set DBP equal to the largest DP(J).]

$$AK(J) = \sqrt{2 - \frac{DP(J)}{DBP}}$$

$$AKK = \sum_{J=1}^{N+NTR} AN(J)*WD(J)*AK(J)$$

Adjusted WD(J) = WD(J)*AK(J)*WD5/AKK

where,

DELPE(J)	= Entrance pressure drop in Jth type flow channel, psi
DELPX(J)	= Exit pressure drop from Jth type flow channel, psi
KTE(J)	= Entrance pressure loss coefficient for Jth type flow channel
KTX(J)	= Exit pressure loss coefficient for Jth type flow channel
g_c	= Gravitational constant = 386 lbm-in./lbf-sec^2
W(J)	= Flow rate in Jth type flow channel, lbm/sec
A(J)	= Flow area of Jth type flow channel, in.^{2}
ρ_E	= Density at entrance to Jth type flow channel, lbm/in.^{3}
ρ_X	= Density at exit to Jth type flow channel, lbm/in.^{3}

SUM	= Sum of pressure drops in all types of flow channels, psi
DBP	= Average pressure drop, psi
N	= Number of different types of fuel element flow channels
NTR	= Number of different types of tie-rod flow channels
AK(J)	= Computational factor for Jth type flow channel
DP(J)	= Pressure drop for Jth type flow channel, psi
WD(J)	= Flow rate for Jth type flow channel, lbm/sec
WD5	= Total reflector flow rate, lbm/sec
AKK	= Computational factor
T_{K+1}	= Temperature of tie-rod module at radius R_{k+1}, ^oR
T_K	= Temperature of tie rod module at radius R_k, ^oR
q_k	= Heat transferred across surface at tie-rod module radius R_k, Btu/sec^3
q'''	= Nuclear heat generation rate in tie-rod module, Btu/in.^{3}-sec
ΔL	= Length of computational increment, in.
U	= Thermal conductance, Btu/m^2-sec-^oR
R_{k+1}	= Radius at tie-rod module radial segment k + 1, in.
R_k	= Radius at tie-rod module radial segment k, in.
h	= Coolant heat-transfer coefficient, Btu/in.^{3}-sec-^oR
K	= Thermal conductivity, Btu/in.-sec-^oR
UTR	= Tie-rod contact conductance, Btu/in.^{2}-sec-^oR
T_m	= Tie-rod centerline temperature, ^oR
T_w	= Tie-rod wall temperature, ^oR
q'''_{TR}	= Tie-rod heating rate, Btu/in.^{3}-sec
RT	= Tie-rod radius, in.
K_{TR}	= Tie-rod thermal conductivity, Btu/in.-sec-^oR
T_b	= Coolant bulk temperature, ^oR

3. Assumptions

a. The reactor core is divided into twelve computational increments.

b. Transport property evaluations are based on inlet conditions to each computational increment.

c. There are as many as five parallel fuel element flow channels and three tie-rod channels, among which flows are balanced so that all flow channel pressure drops are equal.

d. The adiabatic surfaces surrounding each flow channel do not change with power level.

e. Radiant heat transfer, except between the bottom face of the core and the nozzle, is neglected.

f. There is single-phase flow.

g. There is no axial conduction.

h. The entrance and exit pressure drop for each type flow channel is controlled by constant pressure loss coefficients.

i. The fluid flow in the reactor core is always subsonic.

j. There is turbulent flow of coolant.

k. Tie-rod segments are concentric.

l. There may be up to fifteen segments.

m. Thermal conductivity of each tie-rod segment is based on the arithmetic mean of the two boundary temperatures.

F. SUBROUTINE CURVE

Subroutine CURVE is called by Chain 2 as part of the turbopump calculations. The cavitating head characteristics for the AGC Mark III Mod IV Turbopump are contained in this subroutine in the form of a three-dimensional table. From this table, by methods of linear interpolation and an iteration loop, the pump shaft speed may be determined for the demanded head rise and flow rate.

G. SUBROUTINE FLOW

1. Description

Subroutine FLOW is called by the Turbopump Routine from Chain 2. Given the diluent orifice inlet temperature and pressure, the bleed port pressure, and the diluent orifice diameter, this subroutine computes the diluent flow rate and the Mach number at the orifice.

2. Equations

The equations involved in Subroutine FLOW are given below.

$$WD16 = 2683 \frac{\pi}{4} (D16)^2 C\rho_t \sqrt{H_{D1} - H_{D2}}$$

where

ρ_t = fluid density at diluent orifice throat, lb/in.^{3}

C = Vena Contracta area ratio

$H_{D1} - H_{D2}$ = isentropic enthalpy difference between Station 16 and diluent orifice throat, Btu/lb

D16 = diluent orifice diameter, in.

WD16 = diluent flow rate, lbm/sec

3. Assumptions

Flow through the diluent orifice is assumed to be isentropic flow through a sharp-edged orifice.

H. SUBROUTINE GMACH

1. Description

Subroutine GMACH is called by Subroutine TOZZ1 for each increment, I, in the nozzle and skirt. Given the specific heat ratio for the flow on the hot side of the nozzle and the nozzle or skirt expansion or contraction area ratio for the Ith increment, this subroutine computes the hot-side Mach number at that increment. The Mach number is used in Subroutine TOZZ1 to calculate the static temperature and pressure and the adiabatic recovery temperature, at that increment, for use in the hot-side heat-transfer calculations. The implicit equation given below is solved by stepwise iteration techniques.

2. Equation

$$\epsilon = \frac{1}{M}\left[\left(\frac{2}{\gamma + 1}\right)\left(1 + \frac{\gamma - 1}{2} M^2\right)\right]^{\frac{\gamma + 1}{2(\gamma - 1)}}$$

where

ϵ = Nozzle expansion or contraction area ratio [EXPAN(I) or EXPANS(I)]

M = Mach number

γ = Specific heat ratio (GAMA)

3. Assumptions

a. There is isentropic, one-dimensional flow with a constant specific heat ratio.

b. Flow is supersonic in the divergent section of the nozzle, and subsonic in the convergent section.

I. SUBROUTINE HTC1

1. Description

Subroutine HTC1, which is called by Subroutine TUBEL, computes the heat transfer coefficient for a cylindrical channel.

2. Equations

$$h = 0.25\,(Y)\left(\frac{4\dot{w}}{\pi}\right)^{0.8}\left(\frac{1}{d_h{}^{1.8}}\right)\left(\frac{C_p{}^{0.4}\,k^{0.6}}{u^{0.4}}\right)\left(\frac{T_B}{T_W}\right)^{0.55}$$

$$\text{If } \frac{X}{d_h} < 0.81,\ Y = 1.5$$

$$\text{If } \frac{X}{d_h} \geqq 0.81,\ Y = 1 + 0.3\left(\frac{d_h}{X}\right)^{0.7}$$

where

h = heat transfer coefficient, Btu/in.^{2}-sec-^{o}R

$\dot{w}$ = flow rate, lbm/sec

d_h = hydraulic diameter, in.

C_p = specific heat, evaluated at bulk fluid conditions, Btu/lbm-^{o}R

k = thermal conductivity, evaluated at bulk fluid conditions, Btu/in.-sec-^{o}R

u = absolute viscosity evaluated at bulk fluid condition, lbm/in.-sec

T_B = bulk fluid temperature, ^{o}R

T_W = wall temperature, ^{o}R

X = distance from channel entrance to point of calculation, in.

J. SUBROUTINE LINE

1. Description

Subroutine LINE, which is called by Chain 2, computes the pump discharge line pressure drop and temperature change.

2. Equations

The equations used in connection with Subroutine LINE are given below.

$$\Delta P = \left[K + \frac{(FF)L}{D}\right]\frac{W^2}{2\,g_c\,A^2\rho}$$

$$FF = \left(\frac{1}{2\log\left(Re\,\sqrt{FF}\right) - 0.80}\right)^2$$

$$\Delta H = \frac{Q}{W}$$

where

ΔP = pressure drop, lb/in.^{2}

K = bellows pressure, loss coefficient

FF = friction factor calculated from Nikuradse equation

Re = Reynold's number in which the viscosity is evaluated at the bulk fluid temperature

L = line length, in.

D = line diameter, in.

W = mass flow rate, lb/sec

g_c = acceleration of gravity, in./sec^2

A = flow area, in.^{2}

ρ = propellant density, lb/in.^{3}

Q = heat input rate, Btu/sec

ΔH = change in enthalpy, Btu/lb

3. Assumptions

a. The pressure drop and tempeature rise are small enough so that a one-increment calculation is accurate.

b. There is incompressible flow.

c. The fluid kinetic energy is negligible.

d. The heat input rate is constant.

K. SUBROUTINE NOZZLE

1. Description

Subroutine NOZZLE, which is called by Chain 2, sets up the nozzle and skirt computations and balances the flow rates between these two components. The logical arrangement of this subroutine may be seen by referring to Figure 8. If there is no skirt, the subroutine transfers to Subroutine COOLX, which performs the thermal and fluid dynamic calculations for the nozzle, and then returns to the main program. If there is a skirt, the subroutine assumes a flow rate for the nozzle and for the skirt - then transfers to Subroutine COOLX to perform the thermal and fluid dynamic calculations for the nozzle. It then transfers to Subroutine SKIRT which performs these same calculations for the skirt. If the nozzle and skirt pressure drops are equal, the subroutine has converged and so returns to the main program. If they are not equal, the subroutine has not converged, so the flow rates for the nozzle and skirt are readjusted, using the equations given below; beginning with Subroutine COOLX, another iteration is performed. The flow adjustment equations are derived assuming that the pressure drops are proportional to the square of the flow rates - an assumption which is close enough to being valid that convergence is very sure and rapid.

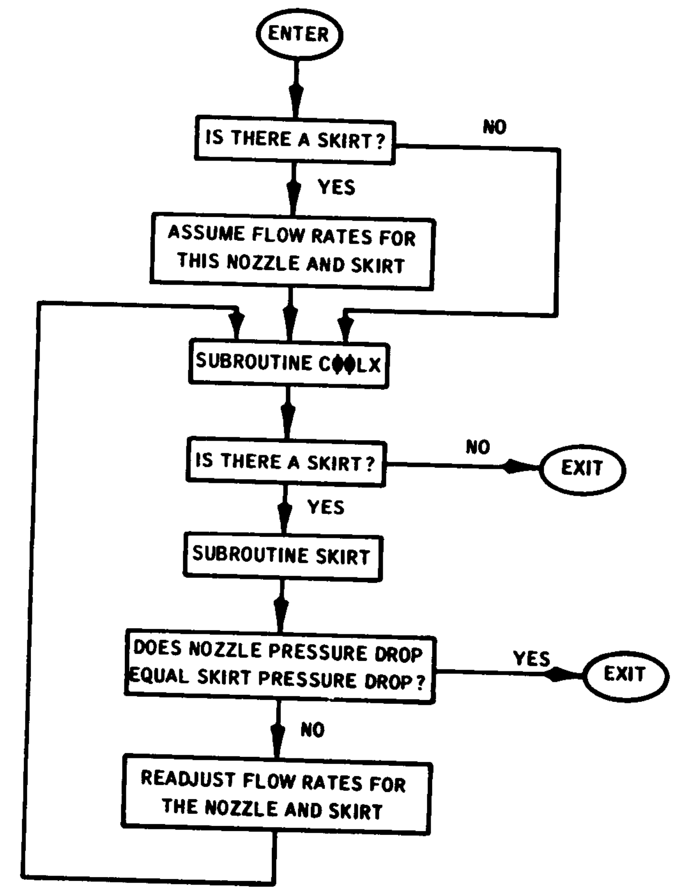

Figure 8

Subroutine NOZZLE Flow Diagram

2. Equations

The equations used in Subroutine NOZZLE are given below.

$$XKN = \sqrt{2\left(1 - \frac{DPN}{DPN + DPS}\right)}$$

$$XKS = \sqrt{2\left(1 - \frac{DPS}{DPN + DPS}\right)}$$

$$XK = (WD3N * XKN) + (WD3S * XKS)$$

$$\text{Adjusted } WD3N = \left[(WD3N * XKN) * WD3\right]/XK$$

$$\text{Adjusted } WD3S = \left[(WD3S * XKS) * WD3\right]/XK$$

where

XKN, XKS and XK = Computational factors
DPN = Nozzle pressure drop, psi
DPS = Skirt, pressure drop, psi
WD3N = Nozzle flow rate, lb/sec
WD3S = Skirt flow rate, lb/sec
WD3 = Total flow rate, lb/sec

3. Assumption

The coolant flows through the nozzle and the skirt sections are in parallel. They have common entrance and exit plenums.

L. SUBROUTINE PERFC

1. Description

If the computed reactor core exit temperature and pressure are within a given tolerance of the input demand chamber temperature and pressure, the program has converged and so it transfers to Chain 2 which calls Subroutine PERFC. This subroutine computes several engine system performance parameters including main chamber thrust, THC, turbine exhaust nozzle thrust, TH19, main chamber specific impulse, ISC, turbine exhaust nozzle specific impulse,

IS19, total engine thrust, THT, net engine specific impulse, ISNET, nuclear power, NP, pressure ratio across turbine power control valve, R, and the angle of opening of the turbine power control valve, BETA. The characteristic velocities are calculated as a function of temperature by an equation developed from data given in Reference 4 . By computing the total flow of energy out of the system minus the total energy into the system, the nuclear power generation is computed. The angle of opening of the turbine power control valve is calculated from an equation of valve angle versus pressure drop developed from the curve of valve characteristics.

2. Equations

The following equations are used in Subroutine PERFC:

$$I_{sp} = \frac{C^* C_F \eta}{g}$$

$$F = I_{sp}\dot{w}$$

$$THT = THC + TH19$$

$$SINET = THT/(WD10 + WD19)$$

$$NP = WD10(HC - H5) + WD21(H6 - H5)$$

where

F = Thrust (THC or TH19), lbf
I_{sp} = Specific impulse (ISC or IS19), sec
C^* = Characteristic velocity (CSC or CS19), ft/sec
C_F = Thrust coefficient (CFC or CF19)
η = Nozzle efficiency (ETANC or ETAN19)
$\dot{w}$ = Mass flow rate (WDC or WD19), lb/sec
g = Acceleration of gravity, ft/sec^2

3. Assumptions

a. Characteristic velocity data taken from Reference 4.

b. Nozzle and skirt heat rejection has negligible effect on performance.

c. Thrust coefficients and efficiencies are independent of chamber temperatures and pressures.

d. There is subsonic flow in the turbine power control valve.

M. SUBROUTINE POW

Subroutine POW is called by Subroutine TOZZ1 at each increment, I, in the nozzle and skirt.

Given the axial distance from the bottom face of the reactor core to a position in the nozzle or skirt coolant tubes, this subroutine obtains a normalized nuclear heat generation rate, QNN, by linear interpolation of a stored table. The nuclear heat generation rates in the nozzle, or skirt, coolant tube, and jacket materials are then obtained, respectively, from the following formulas:

QTPA = QF * BETAA * QNN

QTPB = QF * BETAB * QNN

N. SUBROUTINE POWER

Subroutine POWER is called by Subroutines TUBE1 or TUBE3 at each increment, I, in the reflector, shield, and reactor core.

Given the axial and radial position in the reflector, shield or reactor core, this subroutine determines the nuclear heat generation rate by linear interpolation of stored tables of the normalized power profiles. The normalized radial heat generation rate, VKII, and the normalized axial heat generation rate, VKJJ, thus obtained are used in the following formulas to determine the heat generation rates:

QTP = (QF * VKII * VKJJ)/FV

QTPA = BETAA * QTP

QTPB = BETAB * QTP

where, for each subroutine (REFLEC, SHIELD or CORE), values are obtained from the following tabulation:

	REFLEC	Shield	CORE Fuel Elements	CORE Tie Rod
FV	RFV	SFV	CFV(J)	FVTR(J)
BETAA	BETARA(J)	BETASA	BETACA	BETA(J)
BETAB	BETARB(J)	-	-	-
QTPA	RQTPA	SQTPA	CQTP	QTR3
QTPB	RQTPB	-	-	-

The normalized full power nuclear energy distribution is assumed to apply at all power levels.

O. SUBROUTINE READKM

Subroutine READKM is called by Subroutine TOZZ1, TUBE1, TUBE3, and CORE. For an input material designation number (see Table 2) and temperature, this subroutine supplies the thermal conductivity by linear interpolation of a table of values of thermal conductivity versus temperature for that particular material. The thermal conductivity for the highest temperature in the table is assumed to hold at all higher temperatures. This is done to allow calculations to continue if the range of data is accidentally exceeded during an iteration.

TABLE 2

MATERIAL DESIGNATION NUMBERS FOR SUBROUTINE READKM

Number	
1	Type 347 stainless steel
2	Nuclear grade Beryllium
3	7075-T6 Aluminum
4	Nuclear grade graphite
5	Pyrolytic graphite (perpendicular to basal planes)
6	Lithium hydride
7	A-110-AT Titanium
8	Hydrogen gas
9	Inconel 718
10	Tungsten
11	Inconel X

P. SUBROUTINE REFLEC

1. Description

Subroutine REFLEC, which is called by Chain Three, sets up the reflector thermal and fluid flow computations and balances the flow rates among the flow channels. The logical arrangement of this subroutine may be seen by referring to Figure 9. The subroutine first assumes flow rates for each type of flow channel in the reflector. There may be from one to seven types of flow channels, each of which is computed sequentially in a DØ loop. Next, the entrance pressure drop is computed. The subroutine then branches, depending on whether the channel is a tubular or annular type of channel. The subroutine then begins a DØ loop where for each increment it calls, in succession, Subroutine POW to obtain the nuclear heat generation rate, Subroutine TUBE1 to perform the thermal calculations (if it is a tubular channel) or Subroutine TUBE3 (if it is an annular channel), and finally Subroutine CHANGE to solve the momentum and energy equations.

Next, the exit pressure drop is calculated and the subroutine continues in the DØ loop to calculate the next type of flow channel. After all types of flow channels have been calculated, the channel pressure drops are compared. If all pressure drops are equal, the subroutine has converged and so returns to the main program. If they are not all equal, the subroutine has not converged. In such a case, the flow rates are readjusted, using the equations given below, and another iteration is performed. The flow adjustment equations are derived assuming that the pressure drops are proportional to the square of the flow rates - an assumption which is close enough to being valid that convergence is very sure and rapid.

2. Equations

The equations used in connection with Subroutine REFLEC are given below.

$$\mathrm{DELPE} = \mathrm{KTE}(J)\,\frac{1}{2\,g_c}\left[\frac{W(J)}{A(J)}\right]^2 \frac{1}{\rho_E}$$

$$\mathrm{DELPX} = \mathrm{KTX}(J)\,\frac{1}{2\,g_c}\left[\frac{W(J)}{A(J)}\right]^2 \frac{1}{\rho_X}$$

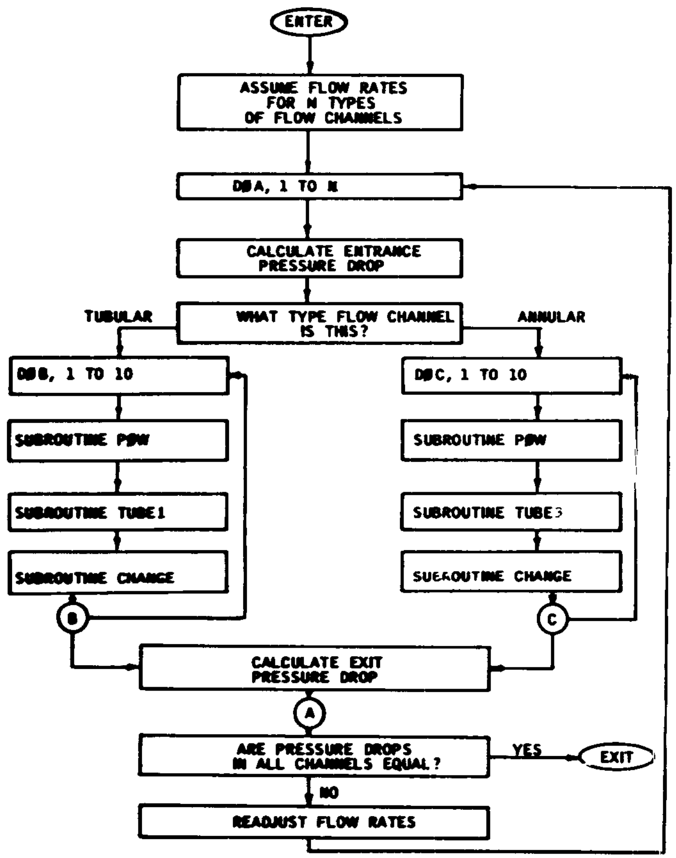

Figure 9

Subroutine REFLEC Flow Diagram

$$SUM = \sum_{J=1}^{M} DP(J)$$

$$DBP = \frac{SUM}{M}$$ [Note: If the largest DP(J) is more than twice DBP, set DBP equal to the largest DP(J).]

$$AK(J) = \sqrt{2 - \frac{DP(J)}{DBP}}$$

$$AKK = \sum_{J=1}^{M} AN(J)*WD(J)*AK(J)$$

Adjusted $WD(J) = WD(J)*AK(J)*WD5/AKK$

where

DELPE(J)	= Entrance pressure drop in Jth type flow channel, psi
DELPX(J)	= Exit pressure drop from Jth type flow channel, psi
KTE(J)	= Entrance pressure loss coefficient for Jth type flow channel
KTX(J)	= Exit pressure loss coefficient for Jth type flow channel
g_c	= Gravitational constant = 386 lbm-in./lbf-sec^2
W(J)	= Flow rate in Jth type flow channel, lbm/sec
A(J)	= Flow area of Jth type flow channel, in.^{2}
ρ_E	= Density at entrance to Jth type flow channel, lbm/in.^{3}
ρ_X	= Density at exit to Jth type flow channel, lbm/in.^{3}
SUM	= Sum of pressure drops in all types of flow channels, psi
DBP	= Average pressure drop, psi
M	= Number of different types of flow channels
AK(J)	= Computational factor for Jth type flow channel
DP(J)	= Pressure drop for Jth type flow channel, psi
WD(J)	= Flow rate for Jth type flow channel, lbm/sec
WD5	= Total reflector flow rate, lbm/sec
AKK	= Computational factor

3. <u>Assumptions</u>

a. The reflector is divided into ten computational increments.

b. Transport property evaluations are based on inlet conditions to each computational increment.

c. There are as many as seven parallel flow channels, among which flows are balanced so that all flow channel pressure drops are equal.

d. The adiabatic surfaces surrounding each flow channel do not change with power level.

e. Radiant heat transfer is neglected.

f. There is single-phase flow.

g. There is no axial conduction.

h. The entrance and exit pressure drop for each type flow channel is controlled by constant pressure loss coefficients.

i. The fluid flow in the reflector is always subsonic.

j. The parallel flow channels may be either equivalent tubes (computed using Subroutine TUBE1), or annular regions (computed using Subroutine TUBE5).

Q. SUBROUTINE SHIELD

1. <u>Description</u>

Subroutine SHIELD, which is called by Chain 3 sets up the shield thermal and fluid flow computations and balances the flow rates among the flow channels. The logical arrangement of this subroutine may be seen by referring to Figure 10.

The subroutine first assumes flow rates for each type of flow channel in the shield. There may be from one to five types of flow channels, each of which is computed sequentially in a DØ loop. Next, the entrance pressure drop is computed. The subroutine then begins a DØ loop where for each increment it calls, in succession, Subroutine POW to obtain the nuclear heat generation

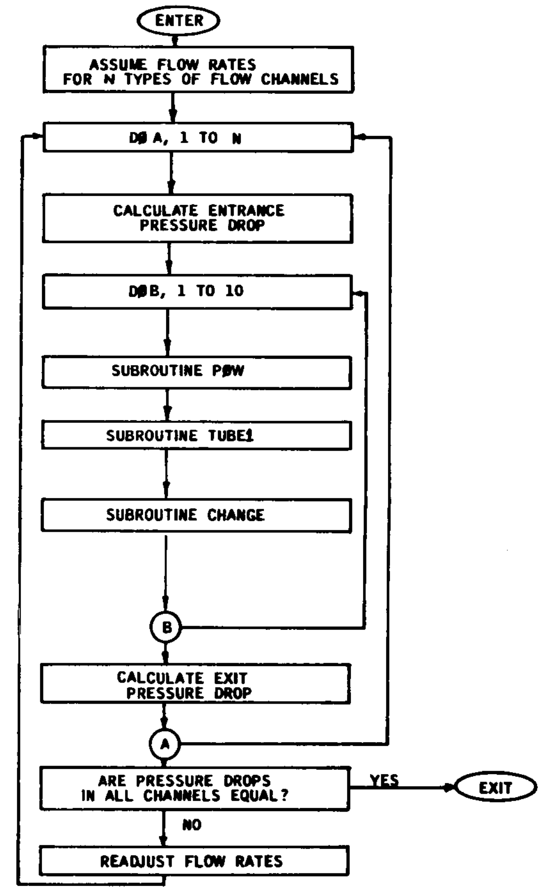

Figure 10

Subroutine SHIELD Flow Diagram

rate, Subroutine TUBE1 to perform the thermal calculation, and Subroutine CHANGE to solve the momentum and energy equations. Next, the exit pressure drop is calculated and the subroutine continues in the DØ loop to calculate the next type of flow channel. After all flow channels have been calculated, the channel pressure drops are compared. If all pressure drops are equal, the subroutine has converged and so returns to the main program. If they are not all equal, the subroutine has not converged; the flow rates then are re-adjusted, using the equations given below, and another iteration is performed. The flow adjustment equations are derived assuming that the pressure drops are proportional to the square of the flow rates, an assumption which is close enough to being valid that convergence is very sure and rapid.

2. <u>Equations</u>

The equations used in Subroutine SHIELD are given below.

$$\mathrm{DELPE} = \mathrm{KTE(J)}\,\frac{1}{2\,g_c}\left[\frac{\mathrm{W(J)}}{\mathrm{A(J)}}\right]^2\frac{1}{\rho_E}$$

$$\mathrm{DELPX} = \mathrm{KTX(J)}\,\frac{1}{2\,g_c}\left[\frac{\mathrm{W(J)}}{\mathrm{A(J)}}\right]^2\frac{1}{\rho_X}$$

$$\mathrm{SUM} = \sum_{J=1}^{M} \mathrm{DP(J)}$$

$$\mathrm{DBP} = \frac{\mathrm{SUM}}{\mathrm{M}}$$

Note: If the largest DP(J) is more than twice DBP, let the largest DP(J) equal DBP.

$$\mathrm{AK(J)} = \sqrt{2 - \frac{\mathrm{DP(J)}}{\mathrm{DBP}}}$$

$$\mathrm{AKK} = \sum_{J=1}^{M} \mathrm{AN(J)*WD(J)*AK(J)}$$

Adjusted $\mathrm{WD(J)} = \mathrm{WD(J)*AK(J)*WD6/AKK}$

where

DELPE(J)	= Entrance pressure drop in Jth type flow channel, psi
DELPX(J)	= Exit pressure drop from Jth type flow channel, psi
KTE(J)	= Entrance pressure loss coefficient for Jth type flow channel
KTX(J)	= Exit pressure loss coefficient for Jth type flow channel
g_c	= Gravitational constant = 386 lbm-in./lbf-sec^2
W(J)	= Flow rate in Jth type flow channel, lbm/sec
A(J)	= Flow area of Jth type flow channel, in.^{2}
ρ_E	= Density at entrance to Jth type flow channel, lbm/in.^{3}
ρ_X	= Density at exit to Jth type flow channel, lbm/in.^{3}
SUM	= Sum of pressure drops in all types of flow channels, psi
DBP	= Average pressure drop, psi
M	= Number of different types of flow channels
AK(J)	= Computational factor for Jth type flow channel
DP(J)	= Pressure drop for Jth type flow channel, psi
WD(J)	= Flow rate for Jth type flow channel, lbm/sec
WDG	= Total shield flow rate, lbm/sec
AKK	= Computational factor

3. <u>Assumptions</u>

a. The shield is divided into ten computational increments.

b. Transport property evaluations are based on inlet conditions to each computational increment.

c. There are as many as five parallel flow channels, among which flows are balanced so that all flow channel pressure drops are equal.

d. The adiabatic surfaces surrounding each flow channel do not change with power level.

e. Radiant heat transfer is neglected.

f. There is single phase flow.

g. There is no axial conduction.

h. The entrance and exit pressure drop for each type of flow channel is controlled by constant pressure loss coefficients.

i. The fluid flow in the shield is always subsonic.

j. The parallel flow channels are equivalent tubes, computed using Subroutine TUBE1.

R. SUBROUTINE SKIRT

Subroutine SKIRT, which is called by Subroutine NOZZLE, performs exactly the same thermal and fluid dynamic computations for the skirt that Subroutine COOLX performs for the nozzle. By referring to the section describing Subroutine COOLX and, in particular Figure 6, the operation of this subroutine may be determined. The operational difference between these two subroutines is that the skirt is divided into only six axial increments of arbitrary length.

S. SUBROUTINE SLOAD

Subroutine SLOAD is called from the main program in Chain 2, immediately after inputing the title card. This subroutine loads cards individually with Columns1-4 (in right adjusted I4 format) giving the array load point; Columns 14-72 give the input values (in E12.8 format). A negative zero input value skips the loading of that value, so that 1-5 input variables per card may be loaded. Loading is sequential, starting with that card's load point. Thus, if Column 1-4 is +010, values are loaded into inputs 10-15. If Column 1-4 of a card is negative, that is the last card loaded and Subroutine SLOAD then returns to the main program. A samples input sheet is shown in Figure 11.

T. SUBROUTINE TOZZ1

1. Description

Subroutine TOZZ1, which is called by Subroutines COOLX and SKIRT, computes the nozzle and skirt heat-transfer coefficients, the wall temperatures, and the rate of heat input to the coolant at a computational increment, I. The Mach number on the hot side of the nozzle is obtained by calling Subroutine GMACH and returning. The equations given below are solved

FORTRAN FLOATING DATA
MAC A1794

ANALYST 1-9	10	14-21	22	DATE 26-33	34	WORK ORDER 38-45	46	JOB NUMBER 50-57	58	PAGE OF 62-69	70	SEQ. 73-80	
CASE 1	-	SAMPLE	-	INPUT	-	TITLE	-	9/30/64	-		-		
001	-	1	+01	2	+01	3	∓01	4	∓01	5	+01		
006	-	6	∓20	70	∓02	3	-01	2	-02	05	∓00		
100	-	0	∓00	5	∓01	600	∓03	20	∓02	21	∓02		
050	-	7	∓01	62	∓00	45	∓01	5	∓00	100	∓03		
009	-	4	∓00	5	∓00	10	∓01	20	∓02	30	∓01		(1)
100	-	0	-	400	∓02	0	-	0	-	0	-		(2)
500	-	1	∓01	2	∓01	3	∓01	4	∓01	5	∓01		(3)
CASE 2	-		-	9/30/64	-		-		-		-		
001	-	11	∓01	0	-	0	-	0	-	55	∓01		
	-		-		-		-		-		-		
UNLOAD TAPE B3 AND RETURN TO BTM					-		-		-		-		
	-		-		-		-		-		-		
	-		-		-		-		-		-		

Figure 11

Sample Input Sheet

assuming values for the unknown wall temperatures. If the calculated values of wall temperature do not agree with the assumed values, the new values are used for the next iteration. This iteration process continues until convergence is reached.

2. **Equations**

The equations used in Subroutine TOZZ1 are given below.

$$h_H = K_4 \left(\frac{4*WD11}{\pi}\right)^{0.8} \left(\frac{1}{D_t^{1.8}}\right)\left(\frac{1}{\epsilon^{0.9}}\right)\left(\frac{C_p^{0.4}\, k^{0.6}}{\mu^{0.4}}\right)_{P_H} \left(\frac{T_{bb}}{T_E}\right)^{0.8}$$

$$h = K_6 \left(\frac{W}{A}\right)^{0.8} \left(\frac{1}{d_h^{0.2}}\right)\left(\frac{C_p^{0.4}\, k^{0.6}}{\mu^{0.4}}\right)_B \left(\frac{T_B}{T_{WC}}\right)^{EXH}$$

$$h_s = \frac{k_s}{t}$$

$$h_r = K_2 \; T_c^2 + T_{wh}^2 \; \left(T_c + T_{wh}\right)$$

$$P_H = \frac{P_c}{\left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{\gamma}{\gamma - 1}}}$$

$$T_{BB} = \left(\frac{T_c}{1 + \frac{\gamma - 1}{2} M^2}\right)$$

$$T_E = T_c + 1/2\,(T_{WH} - T_c) + 0.22\,(T_{HH} - T_c)$$

$$T_{HH} = T_{BB}\left[1 + R\left(\frac{\gamma - 1}{2}\right) M^2\right]$$

where

A = Nozzle coolant tube flow area, in.^{2}

C_p = Specific heat, Btu/lbm-^oR

d_h = Nozzle coolant tube internal diameter, in.

D_t = Nozzle throat diameter, in.

EXH = Variable exponent (for Thompson "A" correlation, EXH = 0.64; for Thompson "B" correlation, EXH = 0.37)

= Local nozzle area ratio

μ = Absolute viscosity, lbm/in.-sec

h = Coolant-side heat-transfer coefficient, Btu/in.^{2}-sec-^oR

h_H = Hot-gas-side heat-transfer coefficient, Btu/in.^{2}-sec-^oR

h_r = Radiation heat-transfer coefficient, Btu/in.^{2}-sec-^oR

h_s = Tube wall heat-transfer coefficient, Btu/in.^{2}-sec-^oR

γ = Specific heat ratio

k = Thermal conductivity, Btu/in.-sec-^oR

K_2 = Thermal radiation factor equal to product of the Boltzmann constant, the emissivity, and the shape factor for thermal radiation between the bottom face of the reactor core and the Ith increment of the nozzle, Btu/sec-in.^{2}-$^oR^4$

K_4 = Variable coefficient which is a function of axial position in the nozzle. It varies because of boundary layer build-up starting at the entrance to the nozzle and because of three-dimensional flow effects.

K_6 = Variable coefficient (for Thompson "A" correlation, K_6 = 0.028; for Thompson "B" correlation, K_6 = 0.023)

k_6 = Tube wall thermal conductivity, Btu/in.-sec-^oR

M = Mach number

P_B = Coolant bulk static pressure, psi

P_H = Static pressure, psi

R = Recovery factor

t = Tube wall thickness, in.

T_B = Coolant bulk static temperature, ^oR

T_{BB} = Hot-side bulk static temperature, ^oR

T_c = Chamber temperature = stagnation temperature, ^oR

T_E = Eckert reference temperature, ^oR
T_{HH} = Adiabatic recovery temperature, ^oR
T_{WC} = Nozzle coolant tube cold-wall temperature, ^oR
T_{WH} = Hot-side tube wall temperature, ^oR
W = Flow rate per nozzle coolant tube, lbm/sec
WD11 = Nozzle flow rate, lbm/sec

3. **Assumptions**

a. Turbulent flow in calculating the heat-transfer coefficients.

b. There is single or two-phase flow.

c. Stagnation temperatures and pressures at all locations in the nozzle are equal to the chamber temperature and pressure.

d. Bartz heat-transfer coefficient with a variable coefficient is used on the hot gas side.

e. Properties in the Bartz heat-transfer correlation are evaluated at the Eckert reference temperature.

f. Isentropic flow used in calculating hot-side static temperature and pressure.

g. Adiabatic recovery temperature used as driving temperature for heat transfer on the hot side.

h. Thermal conductivity of nozzle wall based on arithmetic mean of hot- and cold-side wall temperature.

i. Flat plate geometry used in determining heat transfer across the nozzle wall.

j. No axial conduction.

k. Thermal radiation from the outer surface of the nozzle can be neglected.

l. For purposes of calculating the thermal radiation, the temperature of the bottom face of the reactor core is equal to the chamber temperature, T_c. Radiation shape factors are input, not calculated.

m. There is internal heat generation both in the nozzle tube material and in a jacket material.

U. SUBROUTINE TUBE1

1. Description

Subroutine TUBE1 is called by Subroutines REFLEC, SHIELD, and CORE. Given the channel geometry, the coolant fluid flow rate, and the nuclear heat generation rate, this subroutine computes the wall temperature, the maximum material temperature, and the heat input to the coolant in a thick-walled cylindrical flow channel at a computational increment, I. In general, it is assumed that cylindrical flow channels may be analyzed by drawing an adiabatic surface around the flow channel and replacing the solid material within the surface by a tube of equivalent volume. Where there are a large number of homogeneous channels, this approximation is very good. The heat-transfer coefficient used in the equation below is obtained by calling Subroutine HTC1 and returning. Since a guess must be made of wall temperature to obtain the heat-transfer coefficient, the subroutine iterates on the wall temperature, using the just-calculated value as the value for the next iteration.

2. Equations

The equations used in Subroutine TUBE1 are given below.

$$T_W = T_B + \frac{q'''}{h}\left[\frac{r_o^2 - r_I^2}{2\, r_I}\right]$$

$$T_M = T_W + \frac{q'''}{k}\left[\frac{r_o^2}{2}\ln\left(\frac{r_o}{r_I}\right) - \left(\frac{r_o^2 - r_I^2}{4}\right)\right]$$

$$Q = q''' \, (r_o^2 - r_1^2)\, \pi\, \Delta l$$

where

T_W = Coolant channel wall temperature, ^oR
T_B = Coolant bulk static temperature, ^oR
T_M = Maximum material temperature, ^oR

r_o = Cylinder outer radius, in.
r_I = Cylinder inner radius, in.
Δl = Length of computational increment, in.
Q = Rate of heat addition over computational increment, Btu/sec
q''' = Solid material internal heat generation, Btu/in.^{3}-sec
k = Solid material thermal conductivity, Btu/in.^{2}-sec-^oR
h = Heat transfer coefficient, Btu/in.^{2}-sec-^oR

3. **Assumptions**

a. The thermal conductivity is evaluated at the average of the wall temperature and the maximum material temperature.

b. Adiabatic surfaces do not shift with power level.

c. The equations are for steady-state heat transfer in a thick-walled cylindrical tube in which there is internal heat generation and which is cooled on the inner surface.

V. SUBROUTINE TUBE3

1. **Description**

Subroutine TUBE3 is called by Subroutine REFLEC. Given the channel geometry, the coolant flow rate, and the nuclear heat generation rate, this subroutine computes the wall temperature and the maximum material temperature for both sides of an annular flow channel and the heat input rate to the coolant at a computational increment, I. Each annular flow channel has an inner and outer cooled surface and an inner and outer adiabatic surface. A heat-transfer coefficient is calculated in the subroutine for each cooled surface by assuming wall temperatures. The wall temperatures and maximum temperatures are then calculated and used as values for the next iteration. This iteration process continues until convergence is reached.

2. **Equations**

The equations used in Subroutine TUBE3 are given below.

$$T_W = T_B + \frac{q'''}{h}\left[\frac{r_c^{\,2} - r_A^{\,2}}{2\,r_c}\right]$$

$$T_M = T_W + \frac{q'''}{2\,k_s}\left[r_A^{\,2}\ln\frac{r_c}{r_A} - \frac{\left(r_c^{\,2} - r_A^{\,2}\right)}{2}\right]$$

$$h = 0.25(Y)\left[\frac{\dot{w}}{\pi\left(r_o^{\,2} - r_i^{\,2}\right)}\right]^{0.8}\left[\frac{1}{2\left(r_o - r_i\right)}\right]^{0.2}\left[\frac{C_p^{\,0.4}\,k^{0.6}}{\mu^{0.4}}\right]\left[\frac{T_B}{T_W}\right]^{0.55}$$

If $\dfrac{x}{2\left(r_o - r_i\right)} < 0.81$, $Y = 1.5$

If $\dfrac{x}{2\left(r_o - r_i\right)} \geqq 0.81$, $Y = 1 + 0.3\left[\dfrac{2\left(r_o - r_i\right)}{x}\right]^{0.7}$

$$Q = \pi\,\Delta l \sum_{\substack{\text{both}\\\text{sides}\\\text{of}\\\text{channel}}} q''\left(r_c^{\,2} - r_A^{\,2}\right)$$

where

T_W = Wall temperature for either side of annular channel, ^oR
T_B = Fluid bulk static temperature, ^oR
T_M = Maximum material temperature for either side of annular channels, ^oR
r_o = Radius of outer cooled surface of annular coolant channel, in.
r_{oi} = Radius of inner cooled surface of annular coolant channel, in.
r_c = Radius of either cooled surface, in.
r_A = Radius of either adiabatic surface, in.
Δl = Length of computational increment, in.

q''' = Solid material internal heat generation, Btu/in.^{3}-sec

h = Heat transfer coefficient, Btu/in.^{2}-sec-^oR

k_s = Thermal conductivity of solid material, Btu/in.-sec-^oR

x = Distance from channel entrance to point of calculation, in.

k = Thermal conductivity of coolant fluid, evaluated at bulk fluid condition, Btu/in.-sec-^oR

C_p = Specific heat of coolant fluid, evaluated at bulk fluid condition, Btu/lbm-^oR

M = Kinematic viscosity of coolant fluid, evaluated at bulk fluid condition, lbm/in.-sec

Q = Rate of heat addition per computation increment, in.

3. Assumptions

a. The thermal conductivity is evaluated at the average of the wall temperature and the maximum material temperature.

b. Adiabatic surfaces do not shift with power level.

c. The heat-transfer equations are derived with steady-state heat transfer on both sides of an annular flow channel in which there is internal heat generation in each thick wall of the channel.

V. PROPERTIES DATA

The hydrogen properties data used in this program are based on a set of subroutines developed by O. A. Farmer at Los Alamos Scientific Laboratory and described in References 5 and 6. The LASL subroutines compute enthalpy, density, entropy, specific heat, thermal conductivity and viscosity, when given pressure and temperature in a single phase regime. These subroutines have been used as the basis for Aerojet Azusa Computing Sciences Division Job 0373, Thermodynamic Properties of Para-Hydrogen. Job 0373 enlarges the use of the LASL deck by offering a number of combinations of properties as input, as well as expanding the properties data to include the two phase regime. When an input other than temperature is chosen, an iterative process is performed to determine the temperature.

IV. PROGRAM OPERATION

A. ORGANIZATION

1. Machine and System Requirements

The Nuclear Engine Analysis Program requires an IBM 7090 or 7094 with a FORTRAN II Version II system. The large size of the program created storage problems which forced use of this system.

2. Description

Since the program exceeds the available machine core storage, it is divided into three chains (i.e. links) with each chain calling the succeeding chain into the machine core. A general flow diagram is given in Figure 4.

Chain 1 is on tape unit B2 and Chains 2 and 3 are on tape unit B3. Chain 1 merely loads entropy tables into common and calls Chain 2. Chains 2 and 3 alternate in the machine core, as the computational iteration through the engine system proceeds. Consequently, the tape for tape unit B3 can be kept in a storage bin, after an initial run in which the FORTRAN monitor system will set up the chain tapes. Then, the programer need load only Chain 1, minus its chain control card, plus the data cards, and mount the previously stored tape on unit B3. The data cards should contain the unload card, as mentioned in the input section, to command the dismounting of tape B3 at the completion of a run.

3. Run Time

Run time, of course, depends on the number of system iterations required for convergence, but 5 min per case is adequate for most runs. Each complete system iteration requires approximately 90 sec.

B. INPUT INSTRUCTIONS

The program input requires a title card followed by individually loaded data cards. Each data card contains a right justified, numerical input designation in Columns 1-4 (corresponding to the variable's numerical scatter load designation), followed by five input variables in E 12.8 format. So, if Columns 1-4 contain +300, data will be loaded into inputs 300 - 304. This makes it possible to (1) load "over" a previous input, (2) skip loading a previously defined input by reloading a negative zero, and (3) stop the load process by making Columns 1-4 a negative number. [Refer to Figure 11, for examples of (1), (2) and (3)]. For additional cases, the procedure calls for loading only inputs that are changed from the previous case. If it is desired to unload chain tape B3 and store it, it is necessary to follow the last data card with a card that has UNLOAD in Columns 1-6. This card is printed on-line for the operator to note.

C. SYSTEM OPTIONS

1. <u>Turbopump</u>

The Nuclear Engine Analysis Program is designed to provide three sets of turbopump characteristics which can be obtained by supplying the appropriate inputs. The options available and the appropriate inputs are described below.

a. AGC Mark III Mod IV with cavitating pump characteristics KPUMP = 4 and QILINE = 10^{-5}. (The inputs necessary to describe the turbopump are as follows: C19, A19, A18P6, C18P6.)

b. AGC Mark III Mod IV with non-cavitating pump characteristics KPUMP = 4 and QILINE = 0.0. (Same inputs required as in IV,C,1,a above.)

c. Rocketdyne Mark XV with non-cavitating pump characteristics KPUMP = 15. Necessary inputs for the turbopump description are as follows: C18P9, C18P10, C18P11, C18P12, C19P1, A19P. To stack problems for which KPUMP ≠ 15, behind problems where KPUMP = 15, it is necessary to input C18, C18P2, C18P5, C18P6, C18P7, C19 and A19.)

d. Arbitrary non-cavitating turbopump characteristics. (The inputs required completely describe the head characteristic, efficiency, flow areas, etc., where KPUMP = 1 and QILINE = 0.0. Necessary inputs are as follows: C18, C18P1, C18P2, C18P3, C19, C18P5, C18P6, C18P7.)

2. <u>Diluent</u>

During the initial stage of this program, there was some question as to the best point in the system from which to take the diluent fluid. Therefore, the following options are available:

a. Diluent from the pump discharge (KDUM = 2)

b. Diluent from the reflector inlet (KDUM = 4)

c. Diluent from the shield inlet (KDUM = 6)

3. <u>Skirt Options</u>

Skirt options are as follows:

a. Include a skirt in the nozzle (KSKIRT = +1)

b. No skirt in the nozzle (KSKIRT = -1)

4. <u>Core Options</u>

Core options are as follows:

a. Include tie rods in the core (NTR > 0)

b. No tie rods included (NTR = 0)

c. If tie rods are included, there is an option which allows pressure convergence of the tie rods and fuel

(1) Separately (LTR = +1)

(2) Together (LTR = -1)

It is recommended that, for faster convergence, the tie rods be converged at the same time (LTR = -1).

D. ERROR COMMENTS*

1. <u>Main Routine of Chain 2</u>

a. "DUCT I REJECT, TC = , PC = , P16 = , P2 = "

P16 must be greater than PC for the first guess. Try increasing P16.

*Quotation marks indicate a computer error printout.

b. "Main Program Does Not Converge After ________ Iterations."

The whole system will not converge. Alter the first guesses. Usually P2 is the problem. Increasing KCYCLE is suggested as an alternate course of action.

c. "Neg. Or Zero Net Positive Suction Pressure for TPA, VPSP = "

Try raising the tank pressure, PZ, or lowering the pump inlet line pressure drop by changing input line inputs.

d. "Shaft Speed Does Not Converge, H1D2 = , H1D2P = , SNP = "

This indicates that the program cannot converge on H1D2. The problem could be either with the first guess for SNP or with the pump characteristics not extending into the region of interest.

e. "Turbine Does Not Converge, NØSTAT = "

The turbine power calculation does not converge. Check the turbine input and boundary conditions.

f. "Statement No. _____, K, Pressure, Specific Vol., Enthalpy, Entropy, Quality, Temperature, Specific Heat Ratio, Specific Heat, Conductivity, Viscosity"

Input into properties is bad. Check of calculations of inputs at Statement No. is indicated.

2. SLOAD

"Bad Input"

There is an error in the input cards. Check cards. Remember there can be no input location zero. If this comment occurs, the job will stop immediately and also flush succeeding cases.

3. LINE

"Trouble Calling PRPTY from LINE, Proceeding to Next Case. NØ = , P = , H = , T = "

There is a bad input property; check inputs (P2 and T2) to program.

4. NOZZLE

a. "NOZZLE Does Not Converge"

The subroutine cannot balance the flows between either the nozzle and the skirt or the nozzle and the bolt coolant passage. Check inputs to the routine.

b. "Trouble In Subroutine NOZZLE"

"Statement No. _____, K, Pressure, Specific Vol., Enthalpy, Entropy, Quality, Temperature, Specific Heat Ratio, Specific Heat, Conductivity, Viscosity"

Input into properties is bad. Check calculations of inputs at Statement No. indicated. There is probably a bad flow area.

c. "Trouble In Subroutine NOZZLE:

"Flow Check Not Satisfied. WD3 = , WCHK = , WD3S = , WD3N = "

This comment indicates that all the flow coming in is not coming out. Check the nozzle and flow rate calculations.

5. CØØLX

a. "Trouble Calling PØW From CØØLX. Will Return. QF = , BETAA = , X = "

The program cannot look up the nuclear heat generation rate in nozzle jacket. Probably the area of interest is outside the PØW table.

b. "CØØLX Property. PB = , H5 = "

There is a bad lookup in CØØLX, probably the inlet pressure loss to nozzle is too large.

6. SKIRT

a. "Trouble Calling PØW From SKIRT. Will Return. QF = , BETAA = , BETAB = , X = "

The program cannot look up nuclear heat generation rate in the skirt. Probably the area of interest is outside the PØW table.

b. "SKIRT Property, PB = , H5 = "

There is a bad lookup in SKIRT. Probably the inlet pressure drop to SKIRT is too large.

7. FLØW

a. "Subroutine FLØW Has A Zero Or Negative Delta H

P1 = , T1 = , H1 = , S1 = ,
P2 = , T2 = , HT = , S2 = "

There is a negative or zero pressure drop across the diluent orifice, (i.e., P14 is greater than or equal to P16). Generally it is caused by a bad first guess at P2.

b. "Subroutine FLØW Did Not Converge On Wd,CP After 25 Iterations"

The diluent flow cannot converge if this comment occurs. There has been no trouble with this lately. The calculations concern CP (vena contracta area ratio) as a function of Reynolds Number. Routine FLØW cannot handle a Mach Number greater than 1.02. If this is the problem, the comment "Mach Number Greater Than 1.02" will also be printed.

8. REFLEC

a. "Subroutine REFLEC Did Not Converge After 25 Times Delta P Are Listed Below"

The flow does not balance in parallel channels. Probably there are bad guesses for flow distribution. Also try increasing the iteration counter.

b. "Subroutine REFLEC Has Trouble Calling POWER"

The program cannot look up the nuclear heating rate of the reflector. Probably the area of interest is outside the range of the PØWER table.

c. "Statement No. ____, K, Pressure, Specific Vol., Enthalpy, Entropy, Quality, Temperature, Specific Heat Ratio, Specific Heat, Conductivity, Viscosity"

Input into properties is bad. Check calculations of inputs at Statement No. indicated.

d. "Subroutine REFLEC Has Trouble Calling TUBE3"

There should be a comment previous to this one printed from subroutine TUBE3 giving an explanation. This comment indicates REFLEC was the routine calling TUBE3.

e. "Subroutine REFLEC
Subroutine CHANGE Has Turned Sense Light 1 on Indicating Trouble From PRPTY Routine"

While in subroutine CHANGE, called by subroutine REFLEC, properties were called with bad inputs. This was probably caused by excessive pressure drop or too much heating in the reflector tube.

f. "Subroutine REFLEC
Subroutine CHANGE Has Turned Sense Light 3 On Indicating It Did Not Converge In 25 Tries."

Almost always this is caused by a high Mach Number in the tube, usually because the pressure drop or the heating rate is too high. Try adjusting the reflector dimensions or the heating in the reflector.

9. SHIELD

a. "Statement No. _____, K, Pressure, Specific Vol., Enthalpy, Entropy, Quality, Temperature, Specific Heat Ratio, Specific Heat, Conductivity, Viscosity"

Input into properties is bad. Check calculations of inputs at Statement No. indicated. Quite often this situation develops because in the function $P2 = P1 - \Delta P$, ΔP has turned out to be greater than P1, making P2 negative.

b. "Subroutine SHIELD Did Not Converge After 25 Times Delta P Are Listed Below"

The flow does not balance in parallel channels. Probably there are bad guesses for flow distribution. Also try increasing the iteration counter.

c. "Subroutine SHIELD Could Not Continue Because Of An Error In Subroutine PØWER"

The program cannot look up the nuclear heat generation rate in the shield. Probably the area of interest is outside the range of the PØWER table.

d. "Subroutine SHIELD Could Not Continue Because Of An Error In Subroutine TUBE1"

This error is explained in a comment printed from TUBE1. This comment only identifies Shield as the subroutine calling TUBE1 when the error occurred.

e. "Subroutine SHIELD
Subroutine CHANGE Has Turned Sense Light 1 On Indicating Trouble From PRPTY Subroutine"

While in routine CHANGE, called by routine SHIELD, properties were called with bad inputs. This was probably caused by excessive pressure drop or too much heating in the shield tube.

f. "Subroutine SHIELD
Subroutine CHANGE Has Turned Sense Light 3 On Indicating It Did Not Converge In 25 Tries"

Almost always this is caused by a high Mach Number in the tube which usually comes about because the pressure drop or the heating is too high. Try adjusting the shield dimensions or the heating in the shield.

10. CØRE

a. "Subroutine CØRE Could Not Continue Because Of An Error In Subroutine PØWER"

The program cannot look up the nuclear heat generation rate of the core. Probably the area of interest is outside the range of the PØWER table.

b. "CØRE Does Not Balance"

The program cannot size inlet orifices to balance with the required flow distribution. Check the input and perhaps increase the iteration counter. Since this option has not been used with the engine, there has been no experience in dealing with this problem.

c. "Statement No. ____, K, Pressure, Specific Vol., Enthalpy, Entropy, Quality, Temperature, Specific Heat Ratio, Specific Heat, Conductivity, Viscosity."

Input into properties is bad. Check calculations of inputs at Statement No. indicated.

d. "Subroutine CØRE Did Not Converge After 25 Times Delta P Are Listed Below"

The flow does not balance in parallel channels. Probably there are bad guesses for flow distribution. Also try increasing the iteration counter.

e. "Subroutine CØRE
Subroutine CHANGE Has Turned Sense Light 1 On Indicating Trouble From PRPTY Subroutine"

While in subroutine CHANGE, called by subroutine CØRE, properties were called with bad inputs. This was probably caused by excessive pressure drop or too much heating in the core tube.

f. "Subroutine CØRE
Subroutine CHANGE Has Turned Sense Light 3 On Indicating It Did Not Converge In 25 Tries"

Almost always this is caused by a high Mach Number in the tube which usually comes about because the pressure drop or the heating is too high. Try adjusting the core dimensions or the nuclear heat generation rate in the core.

g. "Subroutine CØRE Could Not Continue Because Of An Error In Subroutine READKM"

READKM cannot return with thermal conductivity. Either it found an invalid material number or it overran the range of the table.

h. "Subroutine CØRE Did Not Converge On TAVG and VKM Using READKM TAVG = , ALPHA = , VKM = , NTRA = , NO = "

Perhaps the input CTR is too high or maybe the nuclear heat generation rate in the tie rod caused it. This error occurred once before with low chamber pressure and chamber temperature inputs. Weeks were spent trying to solve the problem but the reason for this error was not determined.

i. "Subroutine CØRE Did Not Converge On TM"

There is trouble matching the tie rod module boundary temperature ($T_{i,j,k}$) with the fuel element boundary temperature (T_m). Try altering CTR or increasing the counter. Also check to be sure T_m is valid.

j. "Subroutine CØRE Did Not Converge On HTR or HTTR and TB"

The program is unable to compute the heat-transfer coefficient and therefore the gas temperature for the tie-rod channel. Probably this error was caused by bad input geometry.

11. <u>CHANGE</u>

a. "Trouble Calling PRPTY From Subroutine CHANGE. Will Continue.

P = , H = , PB = , TB = ; TB1 = , COMP H = , Q = , WD = ; DH = , HDL = , XA = , XA1 = , COUNT = "

Properties called with bad inputs. Probably this comes about because of either too high a pressure drop or too much heating. CHANGE sets Sense Light 1 "ON," and the calling program checks and comments.

b. "Subroutine CHANGE Does Not Converge After 25 Iterations. Will Return"

PB = , TB = , PB1 = , TB1 = , COMPUTED H = "

Probably the pressure drop or the heating is too high.

12. <u>TØZZI</u>

a. "Routine TØZZI

Statement No., , K, Pressure, Specific Vol., Enthalpy, Entropy, Quality, Temperature, Specific Heat Ratio, Specific Heat, Conductivity, Viscosity"

Input into properties is bad. Check calculations of inputs at Statement No. indicated. This could be a result of bad nozzle geometry or Mach Number could be approaching 1.

b. "Trouble Calling READKM From Subroutine TØZZI. Will Return TAVG = , MK = "

Probably the material number is bad or the region of interest is outside the range of the table.

c. "Routine TØZZI Does Not Converge After 25 Iterations. Will Return

HTC2 = , TCC3 = , TPOS = , TNEG = , TWH = , SUM = , EPP = , TWC = , EPPC = "

The program cannot converge on the nozzle heat-transfer rates. There are several temperature loops where this can happen. Check the heat transfer coefficients, mozzle geometry, temperatures, etc.

13. <u>READKM</u>

"Subroutine READKM

Error Condition in Main Program Will Result When Division By Zero Is Attempted, Or Error Condition Is Indicated by VKM Negative. MFLAGR = , MK = , TAVG = , VKM = "

This is caused by a thermal conductivity with a zero or negative value, which in turn is a result of either overrunning the table or using a bad material number. This comment is a warning only.

14. TUBE1

a. "Trouble Calling READKM From Subroutine TUBE1. Will Call Exit
TAVG = , MK = "

Probably the region of interest is outside the range of the table or else the material number is bad.

b. "Routine TUBE1 Does Not Converge"

This routine computes the maximum temperature in the equivalent tube. There are no suggestions for it not converging since the problem has never occurred.

15. TUBE2

a. "Subroutine TUBE2 Does Not Converge On TW After 25 Tries.
NFLAG = , TWGUESS = , TW = , TWNEW = "

This routine computes the maximum temperature of LiH shield element. A convergence problem has never occurred.

b. "Subroutine TUBE2 Cannot Proceed Because Subroutine HTC1 Returns A Zero For HTC1

NFLAG = , HTC1 = , DSBH = , WHTC1 = , CPTPB = ,
TKTPB = , VUTPB = , HTBTW = , HHTC1 = "

In a case of this kind, all we can suggest is to check the inputs to HTC1.

c. "Subroutine TUBE2 Cannot Proceed Due to Error In Subroutine READKM For Material B"

Probably the READKM table was overrun.

d. "Subroutine TUBE2 Does Not Converge On T1 After 25 Tries.
NFLAG = , TW = , TAVG = , TAVGN = , T1 = ,
KB = "

The program cannot converge on the boundary temperature between solid and liner materials. Perhaps it is bad geometry or an incorrect thermal conductivity.

e. "Subroutine TUBE2 Cannot Proceed Due to Error In Subroutine READKM For Material A"

Probably the READKM table was overrun.

f. "Subroutine TUBE2 Does Not Converge On TM After 25 Tries.
NFLAG = , TW = , T1 = , TAVG = , TAVGN = ,
TM = , KA = "

The program cannot converge on the boundary temperature between solid and liner materials. Perhaps this is a result of bad geometry or of an incorrect thermal conductivity.

16. TUBE3

a. "Subroutine RUBE3 Does Not Converge On TWA After 25 Tries.
NFLAG3 = , TWAGUESS = , TWA = , TWANEW = "

The program cannot compute the inner annulus wall temperature; the $(Tw/Tb)^a$ term in the heat-transfer coefficient must not be converging.

b. "Subroutine TUBE3 Cannot Proceed Because Subroutine HTC1 Returns A Zero For HA, NFLAG3 = , XHTC1 = , DSBH = , WHTC1 = , CPTPB = , TKTPB = , VUTPB = , TB = , TW = , HA = "

Check the HTC1 output and input. Perhaps this situation is a result of bad geometry or other input.

c. "Subroutine TUBE3 Does Not Converge on TWB After 25 Tries.
NFLAG3 = , TWBGUESS = , TWB = , TWBNEW = "

The program cannot compute the outer annulus wall temperature; the $(Tw/Tb)^b$ term in the heat-transfer coefficient must not be converging.

d. "Subroutine TUBE3 Cannot Proceed Because Subroutine HTCL Returns A Zero For HB. NFLAG = , HTC1 = , DSBH = , WHTC1 = , CPTPB = , TKTPB = , VUTPB = , TB = , TW = , HB = "

Check the HTC1 output and input. Perhaps bad geometry or other input is to blame.

e. "Subroutine TUBE3 Cannot Proceed Due to Error in Subroutine READKM For Material A"

Probably the READKM table was overrun.

f. "Subroutine TUBE3 Does Not Converge On TWA After 25 Tries.
NFLAG3 = , TWA = , TAVG = , TAVGNEW = , TMA = , KA = "

The program cannot compute a maximum temperature. It could be the result of geometry or thermal conductivity problems. Also see first error comment under TUBE3.

g. "Subroutine TUBE3 Cannot Proceed Due to Error in Subroutine READKM For Material B"

Probably the READKM table was overrun.

h. "Subroutine TUBE3 Does Not Converge On The TMB After 25 Tries.
NFLAG3 = , TWB = , TAVG = , TAVGNEW = , TMB = , KA = "

The program cannot compute a maximum temperature. It could be the result of geometry or thermal conductivity problems. Also see first error comment under TUBE3.

17. <u>PØW</u>

a. "Routine PØW Given X Value Below Table Values. Will Return X = "

Check input for error or, if correct, extend the table.

b. "Routine PØW Given X Values Above Table Values. Will Return X = "

Check input for error or, if correct, extend the table.

18. <u>PØWER</u>

a. "Subroutine PØWER Has Been Given A Negative Length or Radius.
NFLAGP = , NPART = , RJ = , LI = , KI = , KJ = "

Check input. Length cannot be negative.

b. "Subroutine PØWER No Solution Reached In Table Lookup Of KI.
NFLAGP = , NPART = , LI = , KI = "

Check input for error or, if correct, extend the table.

c. "Subroutine PØWER No Solution Reached In Table Lookup of KJ.
NFLAGP = , NPART = , RJ = , KJ = "

Check input for error or, if correct, extend table.

19. <u>ADJUST</u>

"Subroutine ADJUST Trouble Calling PRPTY Subroutine NAD = ,
K = , P5 = , T5 = "

Properties called with bad inputs. The nozzle exit temperature and pressure are in error. Check back through calculations to see how this happened. It is almost impossible for this to occur.

20. <u>PERFC</u>

a. "No Converge In PERFC
WD CAL = , P30 = , P3OLD = "

The program cannot converge on the pressure drop for the turbine inlet line orifice. Usually this is caused by too high a Mach Number. Try increasing the input D18.

b. "TPCV Blade Angle Greater THAN 90 DEGREES - TPA Is Power Limited."

The turbine cannot supply the power to drive the pump. There is not sufficient pressure available to drive the turbine. Try increasing input D18 or input C18, which is $\frac{\dot{w}\ \ T}{\sqrt{P}}$ for turbine inlet.

c. "PERFØRMANCE

Statement No. _____, K, Pressure, Specific Vol., Enthalpy, Entropy, Temperature, Specific Heat Ratio, Specific Heat, Conductivity, Viscosity"

Properties called with bad inputs. A check of the calculations of inputs at Statement No. is indicated. Probably the error is due to a high Mach Number in the turbine inlet line orifice.

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APPENDIX A

PROGRAM NOMENCLATURE

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I. INPUT DATA LIST

Note: Definitions of all variables are given in Section II (Nomenclature Definitions)

Numerical Designation	Variable	Numerical Designation	Variable
1	C2P1	28	E17PZ
2	C2P2	29	E17P2
3	C2P3	30	E17P6
4	C15P1	31	*
5	*	32	GAMD
6	C15P3	33	D16
7	C15P4	34	TZ
8	GAMA	35	PZ
9	C1P1	36	TCZ
10	A1SQ	37	PCZ
11	GRAV	38	C17P1
12	PA	39	C17P2
13	C18	40	ELIN
14	*	41	DH2
15	*	42	VL
16	E18P4	43	CB
17	C19	44	A19P
18	C14	45	AME
19	C14P1	46	AMX
20	C14P2	47	XKTE
21	*	48	XKTX
22	DH	49	SIGN
23	DH15	50	AK5
24	TW	51	EPRESS
25	D	52	EFLOW
26	DELTL	53	A15
27	E17P1	54	A17

*Input location not used.

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Numerical Designation	Variable	Numerical Designation	Variable
55	E17P3	88	SHG(3)
56	E17P4	89	SHG(4)
57	E17P5	90	SHG(5)
58	BETAA	91	SHG(6)
59	BETAB	92	SHG(7)
60	XK3	93	SHG(8)
61	ENOZ	94	SHG(9)
62	DSBT	95	SHG(10)
63	ECHAN	96	DELL(1)
64	ETUB	97	DELL(2)
65	RECOV	98	DELL(3)
66	DSB(1)	99	DELL(4)
67	DSB(2)	100	DELL(5)
68	DSB(3)	101	DELL(6)
69	DSB(4)	102	DELL(7)
70	DSB(5)	103	DELL(8)
71	DSB(6)	104	DELL(9)
72	DSB(7)	105	DELL(10)
73	DSB(8)	106	EXPAN(1)
74	DSB(9)	107	EXPAN(2)
75	DSB(10)	108	EXPAN(3)
76	THIK(1)	109	EXPAN(4)
77	THIK(2)	110	EXPAN(5)
78	THIK(3)	111	EXPAN(6)
79	THIK(4)	112	EXPAN(7)
80	THIK(5)	113	EXPAN(8)
81	THIK(6)	114	EXPAN(9)
82	THIK(7)	115	EXPAN(10)
83	THIK(8)	116	AK2(1)
84	THIK(9)	117	AK2(2)
85	THIK(10)	118	AK2(3)
86	SHG(1)	119	AK2(4)
87	SHG(2)		

Numerical Designation	Variable	Numerical Designation	Variable
120	AK2(5)	152	CPL
121	AK2(6)	153	CFC
122	AK2(7)	154	ETANC
123	AK2(8)	155	CF19
124	AK2(9)	156	ETAN19
125	AK2(10)	157	E1
126	C11A11	158	E2
127	C18P1	159	XLR
128	C18P2	160	RFV
129	C18P3	161	XLS
130	C18P5	162	SFV
131	C18P6	163	BETASA
132	C18P7	164	*
133	C18P8	165	VLTBP
134	C18P9	166	VLC
135	C18P10	167	*
136	C18P11	168	BETACA
137	C18P12	169	BETACP
138	A19	170	ERSC
139	C19P1	171	RRA(1)
140	CTPV	172	RRA(2)
141	D18	173	RRA(3)
142	QIN	174	RRA(4)
143	*	175	RRA(5)
144	*	176	RRA(6)
145	*	177	RRA(7)
146	*	178	RRB(1)
147	*	179	RRB(2)
148	*	180	RRB(3)
149	DO	181	RRB(4)
150	Q1 LINE	182	RRB(5)
151	Q2 LINE	183	RRB(6)

Numerical Designation	Variable	Numerical Designation	Variable
184	RRB(7)	216	RR(4)
185	RRC(1)	217	RR(5)
186	RRC(2)	218	RR(6)
187	RRC(3)	219	RR(7)
188	RRC(4)	220	CHAN(1)
189	RRC(5)	221	CHAN(2)
190	RRC(6)	222	CHAN(3)
191	RRC(7)	223	CHAN(4)
192	RRD(1)	224	CHAN(5)
193	RRD(2)	225	CHAN(6)
194	RRD(3)	226	CHAN(7)
195	RRD(4)	227	RKTE(1)
196	RRD(5)	228	RKTE(2)
197	RRD(6)	229	RKTE(3)
198	RRD(7)	230	RKTE(4)
199	RRO(1)	231	RKTE(5)
200	RRO(2)	232	RKTE(6)
201	RRO(3)	233	RKTE(7)
202	RRO(4)	234	RN(1)
203	RRO(5)	235	RN(2)
204	RRO(6)	236	RN(3)
205	RRO(7)	237	RN(4)
206	RRI(1)	238	RN(5)
207	RRI(2)	239	RN(6)
208	RRI(3)	240	RN(7)
209	RRI(4)	241	BETARA(1)
210	RRI(5)	242	BETARA(2)
211	RRI(6)	243	BETARA(3)
212	RRI(7)	244	BETARA(4)
213	RR(1)	245	BETARA(5)
214	RR(2)	246	BETARA(6)
215	RR(3)	247	BETARA(7)

Numerical Designation	Variable	Numerical Designation	Variable
248	BETARB(1)	280	RC(1)
249	BETARB(2)	281	RC(2)
250	BETARB(3)	282	RC(3)
251	BETARB(4)	283	RC(4)
252	BETARB(5)	284	RC(5)
253	BETARB(6)	285	RCO(1)
254	BETARB(7)	286	RCO(2)
255	RS(1)	287	RCO(3)
256	RS(2)	288	RCO(4)
257	RS(3)	289	RCO(5)
258	RS(4)	290	RCI(1)
259	RS(5)	291	RCI(2)
260	RSA(1)	292	RCI(3)
261	RSA(2)	293	RCI(4)
262	RSA(3)	294	RCI(5)
263	RSA(4)	295	*
264	RSA(5)	296	*
265	RSB(1)	297	*
266	RSB(2)	298	*
267	RSB(3)	299	*
268	RSB(4)	300	CN(1)
269	RSB(5)	301	CN(2)
270	SN(1)	302	CN(3)
271	SN(2)	303	CN(4)
272	SN(3)	304	CN(5)
273	SN(4)	305	CKTE(1)
274	SN(5)	306	CKTE(2)
275	SKTE(1)	307	CKTE(3)
276	SKTE(2)	308	CKTE(4)
277	SKTE(3)	309	CKTE(5)
278	SKTE(4)	310	CFV(1)
279	SKTE(5)	311	CFV(2)

Numerical Designation	Variable	Numerical Designation	Variable
312	CFV(3)	344	MKBC
313	CFV(4)	345	K CYCLE
314	CFV(5)	346	*
315	*	347	*
316	*	348	*
317	*	349	*
318	*	350	KFLOW
319	*	351	NPNM
320	*	352	*
321	MKAR(1)	353	IDUM
322	MKAR(2)	354	*
323	MKAR(3)	355	KDUM
324	MKAR(4)	356	*
325	MKAR(5)	357	KPUMP
326	MKAR(6)	358	NTUB(1)
327	MKAR(7)	359	NTUB(2)
328	MKBR(1)	360	NTUB(3)
329	MKBR(2)	361	NTUB(4)
330	MKBR(3)	362	NTUB(5)
331	MKBR(4)	363	NTUB(6)
332	MKBR(5)	364	NTUB(7)
333	MKBR(6)	365	NTUB(8)
334	MKBR(7)	366	NTUB(9)
335	NR	367	NTUB(10)
336	NS	368	MK
337	NC	369	MKS
338	KREFIC	370	KSKIRT
339	KSHLD	371	NTUBS(1)
340	KCORE	372	NTUBS(2)
341	MKAS	373	NTUBS(3)
342	*	374	NTUBS(4)
343	MKAC	375	NTUBS(5)

Numerical Designation	Variable	Numerical Designation	Variable
376	NTUBS(6)	408	*
377	*	409	*
378	NTR	410	*
379	KTRPI	411	SKF
380	LTR	412	AK4(1)
381	NTRA	413	AK4(2)
382	NALPHA(1)	414	AK4(3)
383	NALPHA(2)	415	AK4(4)
384	NALPHA(3)	416	AK4(5)
385	NALPHA(4)	417	AK4(6)
386	NALPHA(5)	418	AK4(7)
387	NALPHA(6)	419	AK4(8)
388	NALPHA(7)	420	AK4(9)
389	NALPHA(8)	421	AK4(10)
390	NALPHA(9)	422	AMES
391	NALPHA(10)	423	AMXS
392	NALPHA(11)	424	XKTES
393	NALPHA(12)	425	XKTXS
394	NALPHA(13)	426	BETAAS
395	NALPHA(14)	427	BETABS
396	NALPHA(15)	428	DELLS(1)
397	NALPHA(16)	429	DELLS(2)
398	*	430	DELLS(3)
399	*	431	DELLS(4)
400	*	432	DELLS(5)
401	*	433	DELLS(6)
402	*	434	DSBS(1)
403	*	435	DSBS(2)
404	*	436	DSBS(3)
405	*	437	DSBS(4)
406	*	438	DSBS(5)
407	*	439	DSBS(6)

Numerical Designation	Variable	Numerical Designation	Variable
440	THIKS(1)	472	CHNOTR(2)
441	THIKS(2)	473	CHNOTR(3)
442	THIKS(3)	474	VKTETR(1)
443	THIKS(4)	475	VKTETR(2)
444	THIKS(5)	476	VKTETR(3)
445	THIKS(6)	477	RJJTR(1)
446	EXPANS(1)	478	RJJTR(2)
447	EXPANS(2)	479	RJJTR(3)
448	EXPANS(3)	480	FVTR(1)
449	EXPANS(4)	481	FVTR(2)
450	EXPANS(5)	482	FVTR(3)
451	EXPANS(6)	483	*
452	SHGS(1)	484	*
453	SHGS(2)	485	*
454	SHGS(3)	486	RTR(1)
455	SHGS(4)	487	RTR(2)
456	SHGS(5)	488	RTR(3)
457	SHGS(6)	489	RTR(4)
458	*	490	RTR(5)
459	*	491	RTR(6)
460	SVKTX(1)	492	RTR(7)
461	SVKTX(2)	493	RTR(8)
462	SVKTX(3)	494	RTR(9)
463	SVKTX(4)	495	RTR(10)
464	SVKTX(5)	496	RTR(11)
465	*	497	RTR(12)
466	*	498	RTR(13)
467	RT	499	RTR(14)
468	BETAT	500	RTR(15)
469	*	501	RTR(16)
470	*	502	BETA(1)
471	CHNOTR(1)	503	BETA(2)

Numerical Designation	Variable	Numerical Designation	Variable
504	BETA(3)	532	UTR(15)
505	BETA(4)	533	UTR(16)
506	BETA(5)	534	AK4S(1)
507	BETA(6)	535	AK4S(2)
508	BETA(7)	536	AK4S(3)
509	BETA(8)	537	AK4S(4)
510	BETA(9)	538	AK4S(5)
511	BETA(10)	539	AK4S(6)
512	BETA(11)	540	XK3S
513	BETA(12)	541	SNP(1)
514	BETA(13)	542	SNP(2)
515	BETA(14)	543	SNP(3)
516	BETA(15)	544	ETAP(1)
517	BETA(16)	545	ETAP(2)
518	UTR(1)	546	ETAP(3)
519	UTR(2)	547	RVKTX(1)
520	UTR(3)	548	RVKTX(2)
521	UTR(4)	549	RVKTX(3)
522	UTR(5)	550	RVKTX(4)
523	UTR(6)	551	RVKTX(5)
524	UTR(7)	552	RVKTX(6)
525	UTR(8)	553	RVKTX(7)
526	UTR(9)	554	*
527	UTR(10)	555	*
528	UTR(11)	556	*
529	UTR(12)	557	*
530	UTR(13)	558	*
531	UTR(14)	559	*

II. NOMENCLATURE DEFINITIONS

Note: The numbers following some variables are the numerical designation of input variables as given in the Input Data List.

A1SQ	=	The square of the pump inlet area, in.^{4}	(10)
A15	=	Flow area on the diluent side of the turbine inlet line exchanger, in.^{2}	(53)
A17	=	Flow area on the hot side of the turbine inlet line heat exchanger, in.^{2}	(54)
A19	=	Total throat area of turbine exhaust nozzle, in.^{2}	(138)
A19P	=	Total throat area of turbine exhaust nozzles for the Rocketdyne MK XV turbine, in.^{2}	(44)
AC(J)	=	Flow area of one reactor core fuel element channel of Jth type, in.^{2}	
AK2(I)	=	Thermal radiation factor equal to the product of the Boltzmann constant, the emissivity, and the shape factor for thermal radiation between the bottom face of the reactor core and the Ith increment of the nozzle, Btu/sec-in.^{2}-$^oR^4$	(116 to 125)
AK4(I)	=	Coefficient in the Bartz heat-transfer correlation for the Ith increment of the nozzle.	(412 to 421)
AK4S(I)	=	Coefficient in the Bartz heat-transfer correlation for the Ith increment of the skirt	(534 to 539)
AK5	=	At area ratios less than AK5, the Thompson "B" heat-transfer correlation is used rather than the Thompson "A" correlation	(50)
AME	=	Total inlet flow area of the nozzle coolant tubes, in.^{2}	(45)
AMES	=	Total inlet flow area of the skirt coolant tubes, in.^{2}	(422)
AMX	=	Total exit flow area of the nozzle coolant tubes, in.^{2}	(46)
AMXS	=	Total exit flow area of the skirt coolant tubes, in.^{2}	(423)

AR(J)	=	Flow area of one reflector channel of Jth type, in.^{2}	
AS(J)	=	Flow area of one shield channel of Jth type, in.^{2}	
ATC	=	Total flow area of reactor core fuel elements, in.^{2}	
ATOTAL	=	Total flow area of reactor core, in.^{2}	
ATR	=	Total flow area of reflector, in.^{2}	
ATR(J)	=	Flow area of one reactor core tie-rod channel of the Jth type, in.^{2}	
ATS	=	Total flow area of shield, in.^{2}	
ATTR	=	Total flow area of reactor core tie rods, in.^{2}	

B

BETA	=	Angle of opening of turbine power control valve, degrees	
BETAA	=	Ratio of internal heat generation in nozzle tube material to the normalized internal heat generation	(58)
BETAAS	=	Ratio of internal heat generation in skirt coolant tube material to the normalized internal heat generation	(426)
BETAB	=	Ratio of internal heat generation in nozzle jacket material to the normalized internal heat generation	(59)
BETABS	=	Ratio of internal heat generation in skirt jacket material to the normalized internal heat generation	(427)
BETACA	=	Ratio of internal heat generation in top support plate section of reactor core to normalized internal heat generation	(168)
BETACB	=	Ratio of internal heat generation in reactor core fuel element material to the normalized internal heat generation	(169)
BETA(J)	=	Ratio of internal heat generation for the reactor core tie rod module material between radii RTR(J) and RTR(J + 1) to the normalized heat generation	(502 to 517)
BETARA(J)	=	Ratio, for a channel of Jth type in the reflector, of internal heat generation in equivalent tube material (or in material on inner side of annular region) to normalized internal heat generation	(241 to 247)

BETARB(J) =	Ratio, for a channel of Jth type in the reflector, of internal heat generation in material on outer side of annular region to normalized internal heat generation	(248 to 254)
BETASA =	Ratio of internal heat generation in shield material to normalized internal heat generation	(163)
BETAT =	Ratio of internal heat generation in reactor core tie-rod material to the normalized internal heat generation	(468)

C

C1P1 =	Pump inlet line pressure loss coefficient, $sec^2/in.^5$	
C2P1 =	Coefficient in equation which calculates first guess at pump discharge pressure	(1)
C2P2 =	Coefficient in equation for first guess at pump flow rate	(2)
C2P3 =	Flow rate of fluid drawn from shield inlet plenum for tank pressurization (C2P3 = WD21), lbm/sec	(3)
C11A11 =	$\frac{\dot{w}\sqrt{T}}{P}$, for main chamber nozzle (may be experimental or theoretical value) where, $\dot{w}$ = flow rate, lbm/sec; P = pressure, $lbf/in.^2$; T = temperature, ^oR	(126)
C14 =	First guess for the term $\left(\frac{T_b}{T_w}\right)^{0.15}$ in the heat-transfer correlation for the hot side of the turbine inlet line heat exchanger	(18)
C14P1 =	First guess for the term $\left(\frac{T_b}{T_w}\right)^{0.64}$ in the heat-transfer correlation for the diluent side of the turbine inlet line heat exchanger	(19)
C14P2 =	First guess at turbine inlet line heat exchanger wall thermal conductivity, Btu/in.-sec-^oR	(20)
C15P1 =	Coefficient in equation for first guess at diluent enthalpy. (Refer to Statement 304 of Turbopump routine)	(4)

C15P3 =	Coefficient in equation for first guess at diluent supply pressure. (Refer to Statement 310 of Turbopump routine)	(6)
C15P4 =	Coefficient in equation for first guess at diluent flow rate. (Refer to Statement 324 of Turbopump routine)	(6)
C17P1 =	Hot bleed port pressure loss coefficient, $sec^2/in.$	(38)
C18 =	$\frac{\dot{w}\sqrt{T}}{P}$, for turbine nozzle (see C11A11)	(13)
C18P1 =	First guess at the product, $(ET)\left[1 - \left(\frac{P19}{P18}\right)^{\frac{\gamma-1}{\gamma}}\right]$ (Refer to Statement 55 of the Turbopump routine)	(127)
C18P2 =	Constant for the AGC MK III MOD IV turbine in the equation U = C18P2(N)	(128)
C18P3 =	First guess at the turbine pressure ratio	(129)
C18P5, C18P6, C18P7 =	Coefficients for the AGC MK III MOD IV turbine for the turbine efficiency equation $ET = C18P5\left(\frac{U}{CO}\right)^3 + C18P6\left(\frac{U}{CO}\right)^2 + C18P7\left(\frac{U}{CO}\right)$	(130 - 132)
C18P8 =	$\frac{\dot{w}\sqrt{T}}{P}$, for Rocketdyne MK XV turbine nozzle (see C11A11)	(133)
C18P9 =	Constant for the Rocketdyne MK XV turbine in the equation U = C18P9 (N)	(134)
C18P10, C18P11, C18P12 =	Coefficients for the Rocketdyne MK XV turbine for the turbine efficiency equation $ET = C18P10\left(\frac{U}{CO}\right)^3 + C18P11\left(\frac{U}{CO}\right)^2 + C18P12\left(\frac{U}{CO}\right)$	(135 - 137)
C19 =	$\frac{P}{\dot{w}\sqrt{T}}$, for turbine exhaust nozzles (inverse of C11A11)	(17)

C19P1	=	$\frac{P}{\dot{w}\sqrt{T}}$, for turbine exhaust nozzles for Rocketdyne MK XV (inverse of C11A11)	(139)
CB	=	Pump discharge line bellows pressure loss coefficient, in.$^{-4}$	(43)
CF19	=	Turbine exhaust thrust coefficient	(155)
CFC	=	Main chamber thrust coefficient	(153)
CFV(J)	=	Fraction of reactor core, in Jth type channel, which is solid material = 1 - void fraction	(310 - 314)
CHAN(J)	=	Channel type flag for subroutine REFLEC If CHAN(J) is positive, flow channel type is an equivalent tube If CHAN(J) is negative, flow channel type is an annulus	(220 - 226)
CHNOTR(J)	=	Number of reactor core tie-rod channels of Jth type	(471 - 473)
CKTE(J)	=	Entrance pressure loss coefficient for reactor core fuel element channel of Jth type	(305 - 309)
CN(J)	=	Number of reactor core fuel element channels of Jth type	(300 - 304)
CO	=	Turbine spouting velocity, ft/sec	
CPL	=	Pressure loss coefficient for first segment of pump inlet line, sec^2/in.	(152)
CQTP	=	Internal heat generation rate in reactor core elements, Btu/in.^{3}-sec	
CS19	=	Characteristic velocity for turbine exhaust nozzles, ft/sec	
CSC	=	Characteristic velocity for main chamber nozzle, ft/sec	
CTFV	=	Ratio of vena contract area to orifice throat area for turbine inlet line orifice	(140)
CTR	=	First guess at the fraction of heat, generated in the reactor core tie-rod module, which is transferred to the tie-rod coolant flow	(465)

D

D	=	Mean diameter of wall of turbine inlet line heat exchanger, in.	(25)
D16	=	Diluent orifice diameter, in.	(33)
D18	=	Diameter of turbine inlet line orifice, in.	(141)
DELL(I)	=	Length along contour of nozzle coolant tubes in Ith increment, in.	(96 to 105)
DELLS(I)	=	Length along contour of skirt coolant tubes in Ith increment, in.	(428 to 433)
DELPC	=	Total reactor core pressure drop, psi	
DELPE	=	Nozzle inlet manifold pressure drop, psi	
DELPEC	=	Reactor core entrance pressure drop, psi	
DELPTR(J)	=	Total pressure drop for Jth type reactor core tie-rod channel, psi	
DELPX	=	Nozzle exit manifold pressure drop, psi	
DELPXC	=	Reactor core exit pressure drop, psi	
DELTL	=	Length of turbine inlet line heat exchanger increment, in.	(26)
DH	=	Hydraulic diameter of hot side of turbine inlet line heat exchanger, in.	(22)
DH2	=	Pump discharge line internal diameter, in.	(41)
DH15	=	Hydraulic diameter of diluent side of turbine inlet line heat exchanger, in.	(23)
DO	=	Diluent trim orifice diameter, in.	(149)
DPER	=	Reflector entrance pressure drop, psi	
DPES	=	Shield entrance pressure drop, psi	
DPR	=	Total reflector pressure drop, psi	
DPS	=	Total shield pressure drop, psi	
DPTR(J)	=	Entrance pressure drop for Jth type reactor core tie-rod channel, psi	
DPXR	=	Reflector exit pressure drop, psi	
DPXS	=	Shield exit pressure drop, psi	
DPXTR(J)	=	Exit pressure drop for Jth type reactor core tie-rod channel, psi	
DSB(I)	=	Internal diameter of skirt coolant tubes at the Ith increment, in.	(66 to 75)

DSBS(I)	=	Internal diameter of skirt coolant tubes at Ith increment, in.	(434 to 439)
DSBT	=	Nozzle throat diameter, in.	(62)

E

E1	=	Convergence tolerance for PC, psi	(157)
E2	=	Convergence tolerance for TC, ^{o}R	(158)
E17P1	=	Convergence tolerance for the wall to bulk temperature ratio on the hot side of the turbine inlet line heat exchanger	(27)
E17P2	=	Convergence tolerance for the wall to bulk temperature ratio on the diluent side of the turbine inlet line heat exchanger	(29)
E17P3	=	Convergence tolerance for calculation of the friction factor in subroutine CHANGE	(55)
E17P4	=	Convergence tolerance for pressure drop calculation in turbine inlet line heat exchanger	(56)
E17P5	=	Convergence tolerance on diluent flow rate	(57)
E17P6	=	Convergence tolerance for matching computed bleed port pressure	(30)
E17PZ	=	Convergence tolerance for turbine inlet line heat-exchanger wall thermal conductivity	(28)
E18P4	=	Convergence tolerance for turbine power calculation	(16)
ECHAN	=	Converge··e tolerance used for difference solution of momentum and energy equations in Subroutine CHANGE	(63)
EFLOW	=	Convergence tolerance for Reynolds number in Subroutine FLØW	(52)
ELIN	=	Convergence tolerance for friction factor in Subroutine LINE	(40)
ENØZ	=	Convergence tolerance used for all thermal calculations in Subroutine NOZZLE	(61)
EPRESS	=	Value of differential pressure for computing sonic velocity in subroutine FLØW	(51)
ERSC	=	Convergence tolerances used in Subroutine REFLEC, SHIELD, and CORE	(170)

ET	=	Isentropic turbine efficiency	
ETAN19	=	Turbine exhaust nozzle efficiency	(156)
ETANC	=	Main chamber nozzle efficiency	(154)
ETAP	=	Pump efficiency	
ETAP(1), ETAP(2), ETAP(3)	=	Coefficients for the pump efficiency equation $ETAP = ETAP(1) \left(\frac{Q1}{N}\right)^2 + ETAP(2) \left(\frac{Q1}{N}\right) + ETAP(3)$	(544 to 546)
ETUB	=	Convergence tolerance used for all computations performed in Subroutines TUBE1, TUBE2 and TUBE3	(64)
EXPAN(I)	=	Nozzle expansion ratio at Ith increment If EXPAN(I) is positive, the nozzle area ratio is divergent If EXPAN(I) is negative, the nozzle area ratio is convergent	(106 to 115)
EXPANS(I)	=	Skirt area ratio in Ith increment If EXPANS(I) is positive, the skirt area ratio is divergent If EXPANS(I) is negative, the skirt area ratio is convergent	(446 to 451)
F	=	Turbine power control valve flow coefficient	
FVTR(J)	=	Void fraction for Jth type reactor core tie-rod channel	(480 to 482)

G

GAMA	=	Specific heat ratio	(8)
GRAV	=	Gravitational acceleration = 386.4 in./sec^2	(11)

H

H1D2	=	Pump head rise, ft	
HB15	=	Heat-transfer coefficient on diluent side of turbine inlet line heat exchanger, Btu/$in.^2$-sec-^{o}R	
HB17	=	Heat-transfer coefficient on hot side of turbine inlet line heat exchanger, Btu/$in.^2$-sec-^{o}R	
HC	=	Enthalpy at chamber pressure and temperature, Btu/lbm	

H(I) = Reactor core tie-rod module wall heat-transfer coefficient at Ith increment, Btu/in.^{2}-sec-^{o}R

HHTC2 = Nozzle and skirt coolant side heat-transfer coefficient, Btu/in.^{2}-sec-^{o}R

HHTC3 = Nozzle and skirt hot-side heat-transfer coefficient, Btu/in.^{2}-sec-^{o}R

HN = Enthalpy at station N, where N assumes values as given in Table 1 Station Designations, Btu/lb

HT(I) = Reactor core tie-rod heat-transfer coefficient at Ith increment, Btu/in.^{2}-sec-^{o}R

I

IDUM = Intermediate print flag for turbopump routine

For IDUM = -1, intermediate print out

For IDUM = +1, no intermediate print out

IS12 = Turbine exhaust nozzle specific impulse, lbf-sec/lbm

ISC = Main chamber specific impulse, lbf-sec/lbm

ISNET = Net engine specific impulse, lbf-sec/lbm

J

J = Mechanical equivalent of heat = 9338 in.-lbf/Btu

K

KCORE = Intermediate print out flag for Subroutine CORE (340)

For KCORE = -1, print each iteration

For KCORE = +1, print only converged values

KCYCLE = Maximum number of total program iterations allowed (345)

KDUM = Diluent bleed location flag (355)

For KDUM = 2, diluent bled from pump discharge line

For KDUM = 3, diluent bled from nozzle exit plenum

For KDUM = 6, diluent bled from shield entrance plenum

KFLOW = Intermediate printout flag for Subroutine FLØW

For KFLOW = -1, intermediate print out

For KFLOW = +1, no intermediate print out (350)

KIT = Number of total program iterations

KPUMP = Turbopump configuration flag (357)

For KPUMP = 1, special turbopump characteristics (see statement number 512 of Turbopump routine)

For KPUMP = 4, MARK III MOD 4 turbopump

For KPUMP = 15, MARK XV turbopump

KREFLC = Intermediate printout flag for subroutine REFLEC (338)

For KREFLC = -1, print each iteration

For KREFLC = +1, print only converged values

KSHLD = Intermediate printout flag for Subroutine SHIELD

For KSHLD = -1, print each iteration

For KSHLD = +1, print only converged values (339)

KSKIRT = Flag for skirt calculations (370)

For KSKIRT = -1, there is no skirt on the nozzle

For KSKIRT = +1, there is a skirt on the nozzle

KTRPI = Number of radial segments in reactor core tie rod module (379)

L

LTR = Flag for first guess of reactor core flow distribution (380)

For LTR = +1, initial flow distribution based on flow area only

For LTR = -1, initial flow distribution based on total hydraulic resistance of inlet orifices and channel flow area

MK = Nozzle tube material number (368)

MKAC = Material number for top support plate section of reactor core (343)

MKAR(J) = Reflector channel equivalent tube material number, or material number for inner side of annular region for Jth type channel (321 to 327)

MKAS	=	Shield equivalent tube material number	(341)
MKBC	=	Reactor core fuel element material number	(344)
MKBR(J)	=	Reflector material number for outer side of annular region for Jth type channel	(328 to 334)
MKS	=	Skirt tube material number	(369)

N

N	=	Turbopump shaft speed, rpm	
NALPHA(J)	=	Flag which indicates the mode of heat transfer between radii RTR(J) and RTR (J + 1) of reactor core tie-rod module	(382 to 397)
		For NALPHA(J) = -1, contact conductance	
		For NALPHA(J) = 0, convection	
		For NALPHA(J) = positive integer, the value of which is the material number, designates conduction through solid material	
NC	=	Number of types of flow channels in reactor core fuel elements	(337)
NCORE	=	Subroutine CORE convergence flag	
		For NCORE = 0, subroutine converged	
		For NCORE = 1, subroutine did not converge	
NP	=	Nuclear power, megawatts	
NPRM	=	Number of turbine inlet line heat-exchanger increments	(351)
NPSH	=	Pump inlet net positive suction head, ft	
NPSP	=	Pump inlet net positive suction pressure, psi	
NR	=	Number of types of flow channels in reflector	(335)
NREFLC	=	Subroutine REFLEC convergence flag	
		For NREFLC = 0, subroutine converged	
		For NREFLC = 1, subroutine did not converge	
NS	=	Number of types of flow channels in shield	(336)
NSHLD	=	Subroutine SHIELD convergence flag	
		For NSHLD = 0, subroutine converged	
		For NSHLD = 1, subroutine did not converge	

NTR	=	Number of types of flow channels in reactor core tie-rods (NTR = 0 will cause the tie-rod computations to be bypassed)	(378)
NTRA	=	Reactor core tie-rod material number	(381)
NTUB(I)	=	Number of nozzle coolant tubes at Ith increment	(358 through 367)
NTUBS(I)	=	Number of skirt coolant tubes at Ith increment	(371 through 376)

P

P18/P19	=	Pressure ratio across turbine	
PA	=	Ambient external pressure, psia	(12)
PB	=	Nozzle coolant fluid static pressure, psia	
PBC	=	Reactor core coolant fluid static pressure, psia	
PBR	=	Reflector coolant fluid static pressure, psia	
PBS	=	Shield coolant fluid static pressure, psia	
PBTR(I)	=	Reactor core tie-rod channel coolant fluid static pressure at Ith increment, psia	
PC	=	Chamber pressure, psia	(37)
PN	=	Pressure at station N, where N assumes values as given in Table 1, Station Designations, psia	
PXC(J)	=	Pressure at exit from Jth type reactor core fuel element channel, psia	
PXR(J)	=	Pressure at exit from Jth type reflector channel, psia	
PXS(J)	=	Pressure at exit from Jth type shield channel, psia	
PXTR(J)	=	Pressure at exit from Jth type reactor core tie-rod channel, psia	
POWER	=	Turbopump power, in.-lbf/sec	
PVAP	=	Vapor pressure of propellant in tank, psia	
PZ	=	Propellant tank pressure, psia	(35)

Q

Q1	=	Pump flow rate, gal/min	
Q1(I)	=	Rate of heat input from reactor core tie-rod module wall to coolant at Ith increment, Btu/sec	
QIN	=	Rate of heat input in pump discharge line, Btu/sec	(142)

Q1LINE	=	Rate of heat input in first segment of pump inlet line, Btu/sec	(150)
		Also, flag to indicate use of cavitating characteristics for AGC MK IV MOD IV Turbopump	
		For Q1LINE = 0, use non-cavitating MARK III MOD IV pump characteristics	
		For Q1LINE > 0, use Subroutine CURVE to obtain cavitating pump characteristics	
Q2LINE	=	Rate of heat input in second segment of pump inlet line, Btu/sec	(151)
QDDT	=	Heat transferred in a turbine inlet line heat exchanger increment, Btu/sec	
QF	=	Nuclear power multiplication factor	
QT(I)	=	Nuclear heat generation rate in reactor core tie rod at Ith increment, Btu/sec	
QTPA	=	Nuclear heat generation rate in nozzle tube material, Btu/in.^{3}-sec	
QTPB	=	Nuclear heat generation rate in nozzle jacket material, Btu/in.^{3}-sec-^{o}R	

R

R	=	Pressure ratio across turbine power control valve = P18/P19T	
RC(J)	=	Mean radius from reactor core centerline to Jth type reactor core fuel element flow channel type, in.	(280 - 284)
RCI(J)	=	Inner radius of reactor core fuel element equivalent tube, in.	(290 - 294)
RCØ(J)	=	Outer radius of reactor core fuel element equivalent tube, in.	(285 - 289)
RECOV	=	Recovery factor used to calculate the adiabatic recovery temperature on hot side of nozzle	(65)
RFV	=	Fraction of reflector which is solid material = 1 - void fraction	(60)
RJJTR(J)	=	Mean radius from reactor core centerline to Jth type reactor core tie-rod flow channel, in.	(477 - 479)
RKTE(J)	=	Reflector entrance pressure loss coefficient for Jth type flow channel	(227 - 233)

RN(J)	=	Number of reflector channels of each type flow channel	(234 - 240)
RR(J)	=	Mean radius from reactor core centerline to Jth type reflector flow channel, in.	(213 - 219)
RRA(J)	=	Radius to adiabatic surface of solid material on inner side of a reflector annular region for Jth type flow channel, in.	(171 - 177)
RRB(J)	=	Radius to surface of solid material on inner side of a reflector annular region for Jth type flow channel, in.	(178 - 184)
RRC(J)	=	Radius to surface of solid material on outer side of a reflector annular region for Jth type flow channel, in.	(185 - 191)
RRD(J)	=	Radius to adiabatic surface of solid material on outer side of a reflector annular region for Jth type flow channel, in.	(192 - 198)
RRI(J)	=	Inner radius of reflector equivalent tube for Jth type flow channel, in.	(206 - 212)
RRØ(J)	=	Outer radius of reflector equivalent tube for Jth type flow channel, in.	(199 - 205)
RS(J)	=	Mean radius from shield centerline to Jth type shield flow channel, in.	(255 - 259)
RSA(J)	=	Inner radius of shield equivalent tube for Jth type flow channel, in.	(260 - 264)
RSB(J)	=	Outer radius of shield equivalent tube for Jth type flow channel, in.	(265 - 269)
RT	=	Radius of reactor core tie rod, in.	(467)
RTR(J)	=	Inner radius of the Jth cylindrical segment in the reactor core tie-rod module, in.	(486 - 501)
RQTPA	=	Nuclear heat generation in material of reflector equivalent tube, or in material on inner side of annular region, Btu/in.^{3}-sec	
RQTPB	=	Nuclear heat generation in reflector material on outer side of annular region, Btu/in.^{3}-sec	
RVKTX(J)	=	Reflector exit pressure loss coefficient for Jth type flow channel	(547 - 553)
RW	=	Thermal resistance of turbine inlet line heat exchanger wall, in.^{2}-sec-^{o}R/Btu	

S

S	=	Pump suction specific speed	
SFV	=	Fraction of shield which is solid material = 1 - void fraction	

SHG(I)	=	Thickness of nozzle jacket at Ith increment, in.	(86 - 95)
SHGS(I)	=	Thickness of skirt jacket at Ith increment, in.	(452 - 457)
SIGN	=	Sign of turbopump shaft speed equation, Statement No. 512	(49)
SN(J)	=	Number of shield flow channels of Jth type flow channel	(270 - 274)
SKF	=	First guess at fraction of total nozzle coolant flow which goes through skirt	(411)
SKTE(J)	=	Shield entrance pressure loss coefficient for Jth type flow channel	(275 - 279)
SMP(1), SMP(2), SMP(3)	=	Coefficients describing the pump head characteristics for inputs where KPUMP = 1 (see KPUMP definition and Statement No. 512 in Turbopump routine)	(541 - 543)
SMS	=	Pump specific speed (printed out as NS)	
SQTPA	=	Nuclear heat generation in shield material, Btu/in.^{3}-sec	
T5	=	Nozzle coolant fluid bulk temperature, ^oR	
TBC	=	Reactor core fuel element coolant fluid bulk temperature, ^oR	
TBR	=	Reflector coolant fluid bulk temperature, ^oR	
TBS	=	Shield coolant fluid bulk temperature, ^oR	
TBTR(I)	=	Reactor core tie-rod coolant fluid bulk temperature at Ith increment, ^oR	
TC	=	Chamber temperature, ^oR	
TH19	=	Turbine exhaust nozzle thrust, lbf	
THC	=	Main chamber thrust, lbf	
THT	=	Total engine thrust, lbf	
THIK(I)	=	Thickness of nozzle coolant tubes at Ith increment, in.	(76 - 85)
THIKS(I)	=	Skirt tube wall thickness at Ith increment, in.	(440 - 445)
TM	=	Maximum material temperature of reflector equivalent tube, ^oR	
TMA	=	Maximum material temperature on inner side of reflector annular region, ^oR	

TMAX(I)	=	Reactor core tie-rod centerline temperature at Ith increment, ^oR	
TMB	=	Maximum material temperature on outer side of reflector annular region, ^oR	
TMC	=	Maximum material temperature of reactor core fuel element, ^oR	
TMS	=	Maximum material temperature of shield equivalent tube, ^oR	
TN	=	Temperature at station N, where N assumes values as given in Table 1 Station Designations, ^oR	(541 - 543)
TT(I)	=	Reactor core tie-rod surface temperature at Ith increment, ^oR	
TW	=	Turbine inlet line heat exchanger wall thickness, in. (or wall temperature of reflector equivalent tube, ^oR)	(24)
TW15	=	Wall temperature on diluent side of turbine inlet line heat exchanger, ^oR	
TW17	=	Wall temperature on hot side of turbine inlet line heat exchanger, ^oR	
TWA	=	Wall temperature on inner side of reflector annular region, ^oR	
TWAVG	=	$\frac{TW17 + TW15}{2}$, ^oR	
TWB	=	Wall temperature on outer side of reflector annular region, ^oR	
TWC	=	Wall temperature of reactor core fuel element, ^oR (or nozzle tube cold-side wall temperature, ^oR)	
TWH	=	Nozzle tube hot-side wall temperature, ^oR	
TWS	=	Shield equivalent tube wall temperature, ^oR	
TWTR(I)	=	Reactor core tie-rod module wall temperature at Ith increment, ^oR	
TZ	=	Temperature of propellant in tank, ^oR	(34)

U

U	=	Turbine blade tip speed, ft/sec	
UTR(J)	=	Contact conductance for reactor core tie-rod module between radii RTR(J) and RTR(J + 1), where applicable, Btu/in.^{2}-sec-^oR	(518 - 533)

VKTETR(J)	=	Reactor core tie-rod entrance pressure loss coefficient for Jth type flow channel	(475 - 476)
VL	=	Pump discharge line equivalent length, in.	(42)
VLC	=	Length of reactor core, in.	
VLTSP	=	Thickness of top support plate section of reactor core, in.	(165)

W

WD3N	=	Total mass flow rate in nozzle coolant tubes, lbm/sec	
WD3S	=	Total mass flow rate in skirt coolant tubes, lbm/sec	
WDC	=	Mass flow rate in one reactor core fuel element channel of Jth type, lbm/sec	
WDN	=	Mass flow rate at station N, where N assumes values as given in Table 1 Station Designations, lbm/sec	
WDS(J)	=	Mass flow rate in one shield channel of Jth type, lbm/sec	
WDR	=	Mass flow rate in one reflector channel, lbm/sec	
WFTOT	=	Total mass flow rate through reactor core fuel elements, lbm/sec	
WTR(J)	=	Mass flow rate per channel for reactor core tie-rod channels of Jth type, lbm/sec	
WTRTOT	=	Total mass flow rate through reactor core tie rods, lbm/sec	

X

XK3	=	Fraction of nozzle cold-side tube surface over which heat transfer is assumed to occur	(60)
XK3S	=	Fraction of skirt cold-side tube surface over which heat transfer is assumed to occur	(540)
XKTE	=	Nozzle inlet manifold pressure loss coefficient	(47)
XKTES	=	Skirt inlet manofold pressure loss coefficient	(424)
XKTX	=	Nozzle exit manifold pressure loss coefficient	(48)
XKTXS	=	Skirt exit manifold pressure loss coefficient	(425)
XLR	=	Reflector length, in.	(159)
XLS	=	Shield thickness, in.	(161)